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Comparative Study of Optimized Traditional and Hybrid Buck Converter

By

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M.Sc. Thesis

In

Electronic Engineering

Supervised by

Dr. Ahmad T. Younis

Dr. Ibrahim K. Mohammed

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A Thesis Submitted

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Mohammed Nawaf Ahmed Obied

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Researcher

Abstract

Buck converter is a type of switched mode DC-DC converters that is widely used in power electronic circuits. It is employed to provide a low level output voltage to loads in different applications. In this thesis, two types of Buck converters, classic and switch inductor, are used to deliver a desired voltage to the converter loads. A standard PID controller is used in feedback control system of both kinds of Buck converters. The plant of the Buck converter is mathematically modelled and then the PID controller is designed to regulate the output voltage for the Buck converter.

In this thesis, the PID controller is developed by using Particle Swarm Optimization (PSO) and Artificial Bee Colony (ABC) tuning algorithms, which are employed to obtain optimum values for controller gain parameters. Based on the optimized gain parameters, the PID based Buck converter can send a stable output voltage to the loads. Matlab/Simulink environment is utilized in the simulation process of the voltage controlled classic and hybrid Buck converters.

The conversion behavior of the Buck regulator systems is examined based on all the expected working circumstances, which include variation in source voltage, reference voltage and load resistance, to validate the robustness of the proposed PSO/ABC tuned PID controller. The classic Buck converter is simulated using Matlab software to evaluate the performance of the Buck converter with disturbance. The evaluation process is based on the standard characteristics parameters, which consists of rise time, settling time, maximum overshoot and steady state error. The simulation results show the merit of PSO-PID and ABC-PID controllers in guiding the converter output voltage through the desired input trajectories effectively. However, the Buck converter based on the

ABC tuned PID controller can deliver a faster output voltage than that based on the PSO-PID controller.

The hybrid Buck converter with disturbances is also simulated using the Matlab/Simulink tool and its performance is compared with the results of the PSO-PID controller based classic Buck converter. The simulation results show that the hybrid Buck converter based on ABC tuning method can provide faster drop output voltage with minimal steady state error compared with that of classic Buck converter.

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LIST OF ABBREVIATION

ABBREVIATION	DESCRIPTION
PID	Proportional Integral Derivative
PSO	Particle Swarm Optimization
ABC	Artificial Bee Colony
ACO	Ant Colony Algorithm
LQR	Linear Quadratic Regulator
LQG	Linear Quadratic Gaussian
PP	Pole Placement
FC	Fuzzy Control
FA	Firefly algorithm
MRFT	Modified Relay Feedback Test
PMSG	Permanent Magnet Synchronous Generator
WTS	Wind Turbine System
HWOA	Hybrid Whale Optimization algorithm
GA	Genetic Algorithms
GWO	Grey Wolf Optimization
HEV	Hybrid Electric Vehicles
PWM	Pulse Width Moduulation
LED	Light Emitting Diode
BJT	Bipolar Junction Transistor
TIC	Taylor Instrumental Company
PDF	Probability Density Function
CCM	Continous Condition Mode
DCM	Discrete Condition Mode
UART	Universal Asynchronous Receiver\Transmitter
USB	Universal Serial Bus
ICSP	in-circuit serial programming
MSE	Mean square error
KVL	Kirchhoff’s Voltage Law
KCL	Kirchhoff’s Current Law

LIST OF SYMBOLS

SYMBOL	DESCRIPTION
e (t)	error value
K_p	Proportional gain
K_i	Integral gain
K_d	derivative gain
V_{in}	Input volltage
V_{out}	Output voltage
V_T	The voltage of a transistore
$u(t)$	control action
$\int_0^t e(\tau)d\tau$	the sum of the Instantaneous Error over time (accumulated error)
$\frac{de(t)}{dt}$	error gradient time
p	position
g	global position
w	inertia weight
d	the time during the switch is ON.
1-d	the time during the switch is OFF.
T	switching period
R	Resistance
fs	Switching Frequency
△Vc	Peak to peak output ripple voltage
△I	Peak to peak ripple current
V_{ref}	Reference voltage
L	inductance
C	Capacitance

Chapter One
Introduction and Literature Review

1.1 Overview

In the last four decades, the appropriate use of electrical components has noticeably grown. Currently, there is strong competition among worldwide companies in making the electronic devices smaller aiming at reducing the power consumption and increasing the lifetime of the devices. Every day, the world witnesses introducing new technologies and prototypes are introduced by electronic manufacturing companies. Technologies such as power conversion devices have attracted the attention of many researchers and developers around the world since these topics have played a significant role in the current technological area.

In electrical engineering, power conversion reflects the process of converting the current form of electric-power to another form. The conversion may happen between AC and DC, it also can happen when changing the frequency or voltage (or the combination of both). A power converter is considered an electrical device (or electro-mechanical device) that aims to convert the electrical-power from certain form and level to another depending on the application.

The goal of power electronic converters is to control/process the electric energy flow by controlling/processing the currents and voltages of the system in a way that is optimally appropriated for loads. In the circuit setup, converters use Semiconductor switches, diodes, energy storage elements like inductors, and capacitors.

The production of electrical-power using different power stations can provide an alternating current from the alternator. In practice, users can utilize the electrical-power generated in running a variety of electrical devices. These devices use different voltage levels in an alternating or direct forms with different magnitude levels. Some of the devices need high magnitude voltage level while others need low magnitude voltage level. Based on the aforementioned description, it is necessary to convert such voltages according to the desired requirements, which is the area that converters come into the world of application.

Converters can be categorized based on the type and voltages magnitude level into four types as follows [1]; AC-AC, AC-DC, DC-DC, and DC-AC converters

This thesis deals with the Buck converters of the type of DC-DC. More details about this type of converters will be presented in Chapter two.

1.2 Review of Existing Control Methods for Buck Converters

In the last decades, designing power converters with a good feedback control system capable of Suppling stable output voltage has attracted an attention of many researchers across the world. The literature of voltage controlled Buck converters is considered as one of the activist topics of research in the power electronic field. Many power engineers try to propose and develop optimal designs for Buck converters that are efficient and economically sufficient. Some researchers proposed different controller techniques like Linear Quadratic Regulator (LQR), Linear Quadratic Gaussian (LQG), Pole Placement (PP), Fuzzy Control (FC) etc. to adjust the output voltage of Buck converters.

Csizmadia and Kuczmann [2] designed an LQR controller for the Buck converter that was based on the state feedback. They suggested a method on how select converters parts (e.g., capacitor, inductor, and semiconductor). They also proposed a design of the state feedback in their work. The results showed that their method was robust and efficient.

Sharma and Agarwal [3] used LQG with Buck converter to improve the performance and compensate the impact of load disturbances and the change in input voltage. The proposed design was able to achieve the desired performance as well as obtain minimum cost function in an efficient way.

Andries et al. [4] suggested a PP approach for the Buck converter. The authors tried to improve the performance of the system when having disturbance. Their approach was examined under different conditions and showed an efficient performance compared to other methods in the literature.

Bhat et al. [5] designed an easy and simple approach using FC with Buck converter. They showed that their approach reduced voltage and current ripples, low level of overshoot, and fast-transient response. The approach was efficient in terms of the aforementioned criteria compared to other approaches in the literature.PID has intensively been used to control Buck converters. Most of the methods use traditional control techniques in the design.

Soriano-Sánchez et al. [6] proposed a voltage controlled Buck converter system based on PID controller that was tuned using simple tuning method. Tuning process is based on achieving the required robustness features of the system performance. The approach reflected an acceptable stable and fast regulation capacity compared to other techniques.

Yan et al. [7] suggested an auto-tuning approach using Modified Relay Feedback Test (MRFT) with the Buck converter based on PID controller. The researchers mathematically proved that their design method was satisfacting in terms of the overall performance parameters.

Putri et al. [8] used Permanent Magnet Synchronous Generator (PMSG) and Buck converter with PID controller for a Wind Turbine System (WTS). The proposed method was efficient and stable under different wind speeds. Many other approaches in the literature used traditional tuning methods in optimizing PID controller with Buck converters as in [9][10][11] .

Other researchers work to optimize the controller system for Buck converters by using different numerical optimization approaches. Many of these optimization methods are performed using bio-inspired algorithms.

The study of Helimoglu and Ekinci [12] used a Hybrid Whale Optimization algorithm (H-WOA) in tuning the PID gain parameters used in a Buck converter. The results showed that HWOA method efficiently tuned the controller parameters, which led to achieve a good regulation process in Buck converters.

Another study that was performed by Nishat et al. [13] tuned the parameters of the controller using the concepts of Genetic Algorithms (GA). The authors analyzed the performance of the proposed adjustment approach in terms of the overshoot percentage and settling time parameters. The results showed that the proposed design gave approximately 4.17% of overshoot and 0.0005 s of settling time. They also concluded that the GA algorithm can be efficiently adopted in tuning process of PID parameters used in Buck converters.

This results were proven in the study of Chlaihawi [14], who studied the error criteria and successfully minimized the rise time and overshoot of the converters response. In [15][16][17], GA algorithm is also used to optimize the Buck converters and simulation results have shown the efficient performance of the proposed regulation systems.

Other bio-inspired algorithms can also be used in the optimization of the PID controller with Buck converters.

Furat [18] proposed a regulation approach that used the ABC algorithm where a three-channel cost function was utilized to separately search for optimum value of each of the controller parameters. The reason behind using a three-channel was because the single cost function did not reflect the different impact of each parameter. The output response showed the efficient of the converter performance, which was also confirmed in [18].

Civelek et al. [19] used the ACO algorithm to optimize the PID controller in Boost converter system. The approach showed an acceptable regulation performance in terms of overshoot, settling and rise times based on using the Mean Squared Error as the cost function.

The authors Sonmez et al. [20] benchmarked the performance of the ABC-based versus the GA-based approaches. They performed several simulations for Buck converter using GA and ABC algorithms and found that the ABC algorithm can provide best performance in terms of steady-state error and settling time parameters compared with that of GA tuning method.

Furthermore, the Particle Swarm Optimization algorithm (PSO) has also been used in optimizing PID controllers with Buck converters. This algorithm has proven its efficiency in optimizing controllers.

Alma'aitah et al. [21] proposed a tuning method for PID controller parameters used in Buck converter system using PSO algorithm . The authors tested the regulation performance of the proposed PSO-PID controller based on varying the input voltage and the output load resistance. The simulation results showed the ability of the proposed approach to stabilize the converter output voltage.

Another work proposed by Borin et al. [22] utilized the PSO algorithm to develop fixed gains of PID controller. They minimized the deviations to the desired level, which mitigated the time consumed to obtain the required gains.

Arora et al. [23] used also the PSO algorithm to tune the gain parameters of PID controller used in Buck converter. The proposed approach successfully enhanced the stability of the used system. Also, the approach was tested with a variety of loading conditions. The PSO algorithm can also be used in speeding up the tracking of the input and minimizing the duty cycle.

This case was experimented by Tumari et al. [24], who involved the PSO algorithm in the design of the PID controller with Buck converters. They used a derivative filter in their suggested tuning technique using PID controller. They found the optimal gains when implementing a priority-based fitness on the PSO algorithm.

Ekinci et al. [25] presented a hybrid version of the PSO algorithm (called Hybrid Firefly HF-PSO) to achieve system stability by testing the frequency and time domains of the output response. They also tested the hybrid PSO approach against Grey Wolf Optimization (WOA) and GA algorithms. They found that the PSO algorithm gave more efficient performance compared to the WOA and GA algorithms.

The use of bio-inspired algorithms in tuning the parameters of PID controllers implemented in Arduino has been studied in several works. This is because of the efficiency of these algorithms in providing better optimization outcomes.

Musyafa et al. [26] proposed an approach that used Arduino with a PSO-based PID controller in obtaining the best values for control parameters. The performance of the controller system was assessed based on characteristic parameters such as settling, rise, peak, and delay times.

The pratical results reflected the efficiency of the proposed PID controller in regulation process of Buck converter.

Moreover, Zakki et al. [27] designed and implemented an optimized PID controller in Arduino for Buck converter based on PSO algorithm. The parameters of the controller are tuned in real time aiming at tuning the parameters of the PID controller. The PSO optimization approach has also other advantages such as the tuning procedure needed fewer steps due to the offline system identification, as it was automated, consumed less power, and low memory space.

Anead et al. [28] suggested a control system for nanofluid system using optimized PSO-PID controller implemented in Arduino electronic. The pratical results showed that the proposed controller system succeeded in providing accurate and efficient outcomes in terms of output response and reliability. Furthermore, the study included comparing the performance of the control system using PSO algorithm with that of other bio-inspired algorithms.

In the study of Oliveira et al. [29] implemented PID controller in Arduino electronic system for Buck converter. The parameters of the controller are tuned using two optimization techniques , PSO and GWO. optimized based on of implemented PID controller system in A the performance characteristics PSO algorithm with the Grey Wolf Optimization (GWO) algorithm under the PID in Arduino. The results showed that the PSO algorithm minimized the cost function more than the GWO algorithm.

Another PID control system was proposed in [30] for robot arm. The controller is optimized using three bio-inspired algorithms namely, PSO, ABC, and Firefly (FA) algorithms. The output results of the robot system based on these tuning methods are presented and then compared. The results showed that the optimization method succeeded in tuning the

PID parameters with some advantage to the PSO algorithm. Table 1.1 presents a summary of the aforementioned works.

Table 1.1: Literature review summary of bio-inspired methods

Reference	Year	Methodology	Applications
Anead et al. [28]	2021	PSO	Evacuated tube solar collector
Furat [18]	2021	ABC	Motors
Helimoglu and Ekinci [12]	2020	H-WOA	General in power electronics
Nishat et al. [13]	2020	GA	General in power electronics
Chlaihawi [14]	2020	GA	General in power electronics
Oliveira et al. [29]	2020	GWO and PSO	Temperature control applications
Arora et al. [23]	2020	PSO	Hybrid renewable energy system
Alma'aitah et al. [21]	2019	PSO	Photovoltaic system, uninterruptible power supplies, and electric vehicle
Borin et al. [22]	2019	PSO	Small satellites application
Moshayedi et al. [30]	2019	PSO, ABC, FA	Path planning and trajectory tracking of a mobile robot
Tumari et al. [24]	2019	PSO	Motors
Ekinci et al. [25]	2019	HF-PSO	General in power electronics
Musyafa et al. [26]	2019	PSO	Wind Turbine Power Control System
Zakki et al. [27]	2019	PSO	Solar MPPT system
Civelek et al. [19]	2019	ABC	General in power electronics
Sonmez et al. [20]	2015	ABC	General in power electronics

According to the literature, there exist some limitations and drawbacks in the presented control methods as the regulation performance of most of these approaches are not tested based on working circumstances such as a sudden change in the input voltage or in load resistance and reference variation. Moreover, some of the proposed controllers are tuned manually using trial and error procedure that consumes more time and effort and others are turned using classic optimization methods such as GA method, where there is no gurantee that the obtained values for controller parameters are the best. In this thesis, a simple PID controller technique is adopted to control the output voltage of two types of converters, namely, classic and switched inductor Buck converters, under various working circumstances. The gain parameters of the proposed controller are tuned effectively using both of PSO and ABC tuning algorithms. The voltage regulation process of the Buck converter is evaluated based on uncertainties conditions such as variation in supply voltage, reference voltage and load resistance.

1.3 Motivation

The motivations behind working on this thesis can be summarized by the following:

- Buck converters are involved because they are widely used in a variety of the everyday applications such as smartphones, PCs etc.
- Buck converters are used to step down the voltage in a stable way .
- Buck converters can provide better and steadier performance when integrating a control system in the design. Therefore, it is interesting to work on this integration and gain the required efficiency in term of the gained voltage.

1.4 Contributions

In this thesis, the contributions can be summarized as follows:

1. A classic Buck converter with PID feedback control system is designed and simulated using Matlab script and simulink

environment. Control criteria, which includes rise time, settling time, overshoot and steady state error parameters, are used to assess the performance of the poroposed controller.

2. The performance of PID controller is optimized through using PSO and ABC optimization algorithms, which are used to find optimum values of its gain parameters.
3. In this thesis, hard working conditions which consists change in the reference voltage, input voltage, and load resistance, are adopted in investigation of the robustness of the proposed optimized PID controller.
4. Switched-inductor Buck converter based on hard working disturbances is designed and optimized using PSO and ABC tuning algorithms at having a more efficient response in stepping down the voltage compared to the classical Buck converters.
5. The simulation design of classic converter is verified through the real-time implemention of the ABC-PID controller using Arduino device.

1.5 Thesis Organization

This thesis is organized as follows:

In chapter one, an overview of power converters and a review of existing control methods for Buck converters, in addition to motivation and contributions in work this thesis.

Chapter two presents, theoretical background and information about voltage controlled Buck converters, PID controller technique, PSO and ABC optimization mehods.

In chapter three, a structure configuration and working modes of classic DC-DC Buck converter are stated. The mathematical modeling of the traditional Buck converter system is presented. State space representation of the converter is also included in this chapter.

Chapter four provides simulation of the proposed classic Buck converter using PID controller based on two optimization algorithms, PSO and ABC. Voltage regulation of the Buck converter under working disturbances is discussed and simulation of a switched inductor Buck converter based on PSO/ABC tuned PID controller system is also considered. Voltage adjustment process of the hybrid Buck converter with uncertainties is included and compared with that of the classic converter in this chapter.

In chapter five, the thesis is concluded and summarized. This chapter provides recommendations to developers and designers, and finally, the future vision of this work in terms of development is presented.

Chapter Two
Theoretical Background

2.1 Overview

This chapter presents definitions, types and applications of power converters. It also introduces theory and information of DC-DC Buck converters and PID controller technique. Background and optimization procedure of PSO and ABC tuning methods are also stated in this chapter. Finally, database and technical information of Arduino electronic device used in real-time implementation of the PID controller system is included.

2.2 DC-DC Converters

The DC-DC type of converters has been widely utilized in industrial and commercial applications. For instance, conversion systems of renewable energy, the devices used in electric traction, and more widely in power supplies. A recent statistic estimated that approximately 70% of the consumed power is mainly processed by electronic technologies and devices [1][31]. Furthermore, the recent decade has witnessed increasing in power density and processing capacity of converters, which has directed the research trends to focus on the economic aspects aiming at minimizing the costs [31]. A DC-DC converter is an electric circuit that is able to convert the level of DC voltage to another level [1]. The most common applications of such converters can be ranged from laptop computers, smartphones that use batteries as their main sources of power, to the applications that deal with heat control in manufactures, lighting systems of cars, to mention a few [32][33].

2.3 DC-DC Converters Types

The DC-DC converters can be in six types as follows:

1. **Buck Converters:** This type aims to step down or lower the input DC voltage to a stable output DC voltage [34]. More details about the concept, performance, development of this kind of converters will be elaborated in this thesis. The electric circuit of Buck converter is shown in figure (2.1).

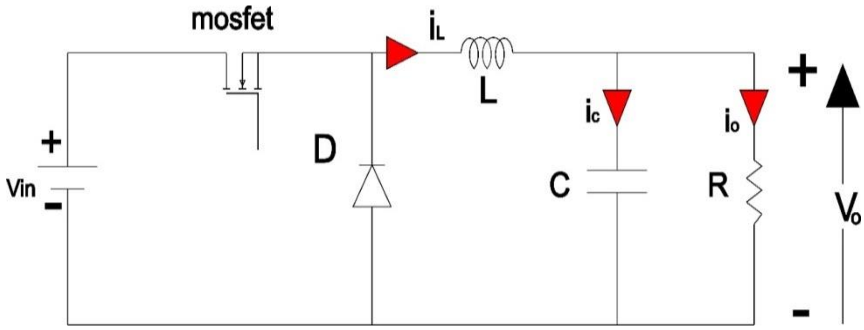


Figure 2.1:Schematic diagram for a Buck Converters

2. **Boost Converters:** It aims to perform a step-up to the input DC voltage to a higher level output DC voltage ,It contains at least two semiconductors (e.g., transistor and diode) and at least one power storage element (capacitor, inductor, or both) [35]. The applications of this type of converters variy from the battery power systems in electric cars (e.g., Toyota Prius HEV system) to the portable lighting systems. Figure (2.2) shows the electric circuit of the Boost Converter.

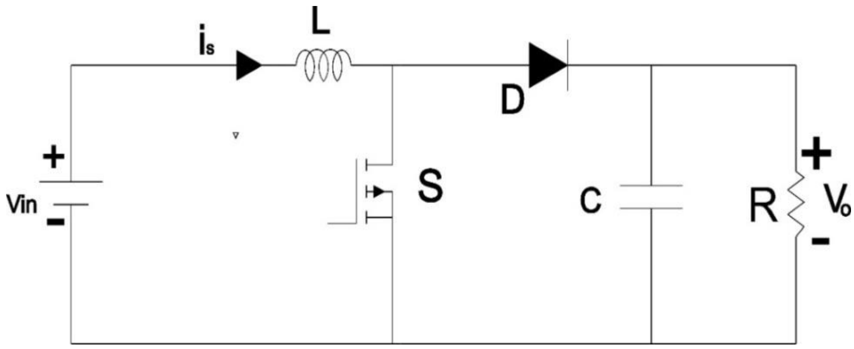


Figure 2.2: Schematic diagram for a Boost Converters

3. **Buck-Boost Converters**: This is a combination of the previous two types. In this combination, the produced converter has an output voltage that is less or even greater than the input voltage magnitude [36]. In this type, instead of using a transformer, it uses a single inductor. Moreover, the Buck-Boost converters work in two modes; continuous conduction mode and discontinuous conduction mode. The most common applications of Buck-Boost converters are in self-regulating power supplies, and many industrial applications [37]. Figure (2.3) shows the electric circuit of the Buck-Boost Converter.

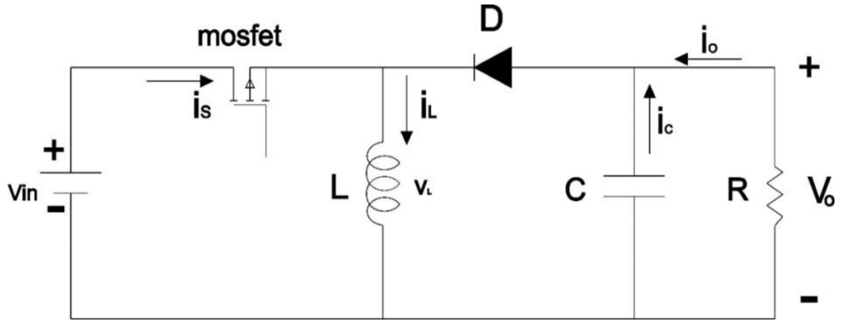


Figure 2.3: Schematic diagram for a Buck-Boost Converters

4. **Cuk Converters**: Similar to the previous one, a Cuk converter is a combination of Buck and Boost converters but with zero-ripple current [38]. It also has a continuous and discontinuous working mode. This type can be used in many applications such that, it can be used in regulating the voltage when having different speeds of winds in the solar-wind systems [38]. The electric circuit of Cuk converter is shown in figure (2.4).

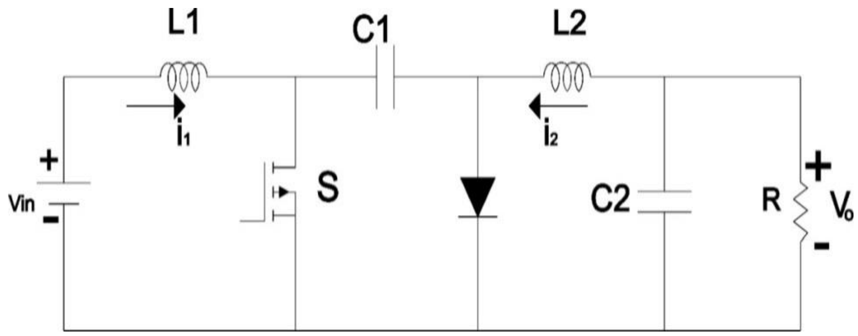


Figure 2.4: Schematic diagram for a Cuk Converters

5. **SEPIC Converters**: The name stands for Single-Ended Primary-Inductor Converter. This type has the ability to regulate the output voltage to be less, greater, or even equal to the one in the input DC voltage. The output of the converter is mainly controlled by a pulse Width Moduulation (PWM) signal with different duty cycle [39]. It has many applications such as LED (Light Emitting Diode) systems, battery-operated equipment in mobile devices, and the suppliers that provide a wide range of input DC voltages. The electric circuit of SEPIC converter is shown in figure (2.5).

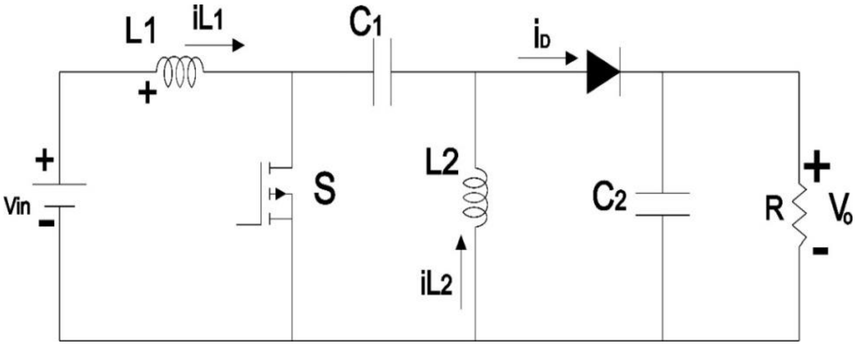


Figure 2.5: Schematic diagram for a SEPIC Converters

6. **ZETA Converters:** This type of converters provides a positive output DC voltage from a DC input voltage that varies below and above the output. It needs a series of capacitors and two inductors; therefore, it is sometimes called flying capacitor and can be used in solar grid circuits [40]. Figure (2.6) shows the electric circuit of the ZETA Converter.

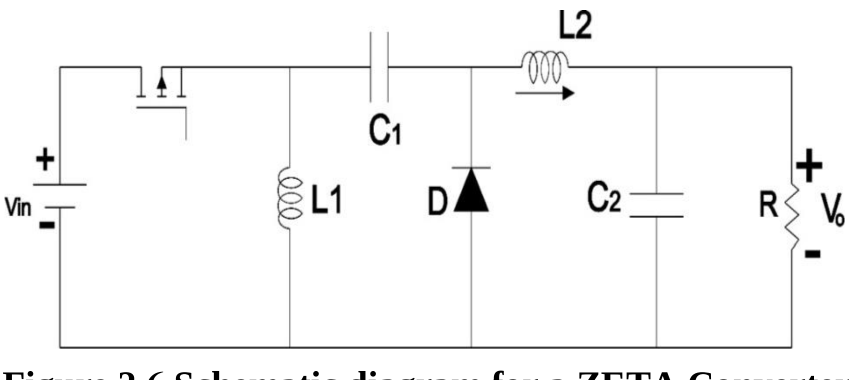


Figure 2.6 Schematic diagram for a ZETA Converters

Generally, the power conversion systems are classified into linear mode and switched-mode regulators. All the above converters are switched-mode voltage regulators. Question may be raised: Why do not developers use a linear instead of switching regulators in voltage reduction?

The linear type has been proven to be efficient compared to the switching type mostly in two cases as follows; a) if the output is lightly loaded, or b) if the output voltage desired is very close to the source level of voltage. Moreover, the linear type usually cancelled the magnetic circuit, instead, it uses inductors or transformers, which results to having smaller circuits. Besides, when the linear type is involved, the Bipolar Junction Transistor (BJT) that is used in the regulation process. In this case, there will be a power loss that leads to the voltage production to be dropped across the transistor input/output terminals as well as the current flowing through it. Avoiding such a situation, it is needed to use switching regulators.

2.4 Buck Converters

Buck converters or called step-down converters are considered a DC-DC switch-mode power supply system. The main purpose of this type is to lower (or Buck) the input DC voltage to a stable lower output DC voltage [34]. Moreover, Buck converters can be integrated with what is called Boost-Converter aiming at producing a Buck-boost converter that is able to provide regulated DC output from either lower or higher voltage than the regulated output. There are two main types of Buck converters.

2.4.1 Classical Buck converter

The classical kind of Buck converters is simple in terms of concept and topology. It is widely and efficiently used as a voltage regulator. Practically, adding additional components (e.g., capacitors or inductors [41]) to a classical Buck converter will lead to having a large number of converter topologies with a high ratio of voltage conversion [42].

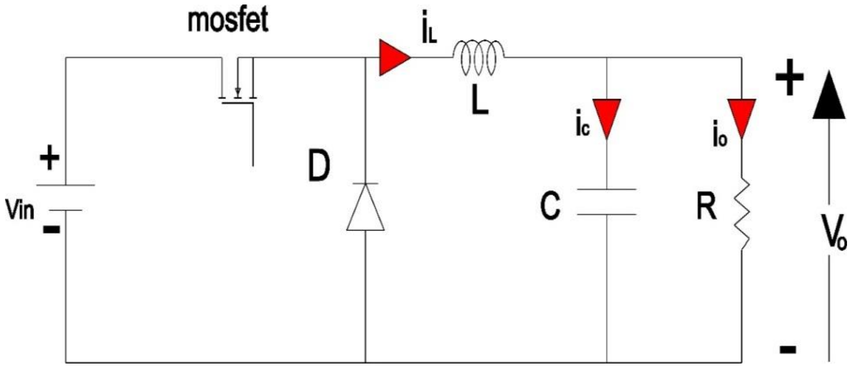


Figure 2.7: A classic circuit diagram of a Buck converter.

2.4.2 Hybrid Buck converter

With the advent of the new technological devices, the field of power electronics has become dominant and more dependent [43]. Recently, with the current technological revolution, the classical Buck converters cannot provide us with the required performance due to the development of devices (e.g., mobile devices). Therefore, hybrid Buck converters have been introduced and developed. This kind of converter provides us with fast transient response with seamless loop transition automatically [44]. Most of today's devices (e.g., electric tools, smartphones, tablets, laptops, etc.) use hybrid Buck converters. Moreover, fast response and high-efficiency circuitry are the central and core needs for any electronic device. Hybrid Buck converters can be considered a unique invention that allows having a steadier supply under a fast-switching environment.

In fact, this is extremely crucial for advanced computing, power management, and other purposes.

Furthermore, inductors and capacitors can be used with Buck converters for the purpose of increasing efficiency [45]. Inductors and capacitors are mainly utilized to control and transfer the input to the output based on the current state of the switch. In OFF state, no power is provided by the source, else the inductor is the voltage source [46]. In a Buck converter, the energy storage in the inductor is controlled by the switch. Here, the inductor is considered the current source aiming at keeping the output capacitor charged [47]. The capacitor can reduce the ripples in the output. In this case, it waves-off the output by filtering the harmonic currents away from the load [48].

According to the aforementioned description, the Buck converters can be used for high efficiency over a large load current range as well as for fast load line transient response [49]. For instance, the load of a PC motherboard is regulated to 5v or 3.3v in order to harmonic the integrated circuits. In this case, there is a constant level of voltage unlike the batteries, where the voltage declines after a period of operation. Thus, different levels of voltage can be gained on the same circuit with the use of switched modes. Here, the switching process is controlled by the signals of the Pulse Width Modulator (PWM). Moreover, bio-inspired algorithms and computations can be involved to optimize the regulation systems in terms of the parameters used. In literature review in Chapter one, more optimized DC-DC converter systems are presented in which different tuning techniques are adopted to make more their regulation performance more efficient and stable.

2.4.2.1 Working Modes

The Hybrid “switched nductore” DC-DC Buck converter work in two modes [50]. Fig 2.8 presents the circuit diagram of the hybrid Buck DC-DC converter.

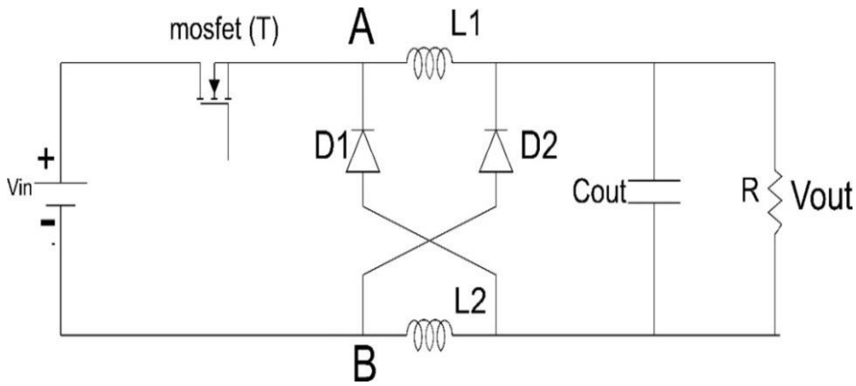
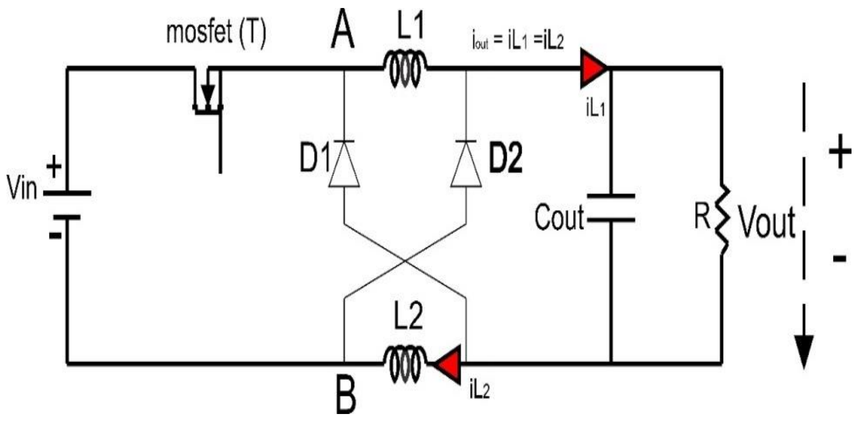


Fig.2.8. Hybrid Buck DC-DC converter

(i) mode 1

In this working mode the circuit of hybrid Buck converter is shown in figure (2.8.a) the switch mosfet is in close and D1, D2 are in off state where the inductor L1 and L2 are connected in series , and charge during the period of this mode (t_{on}).

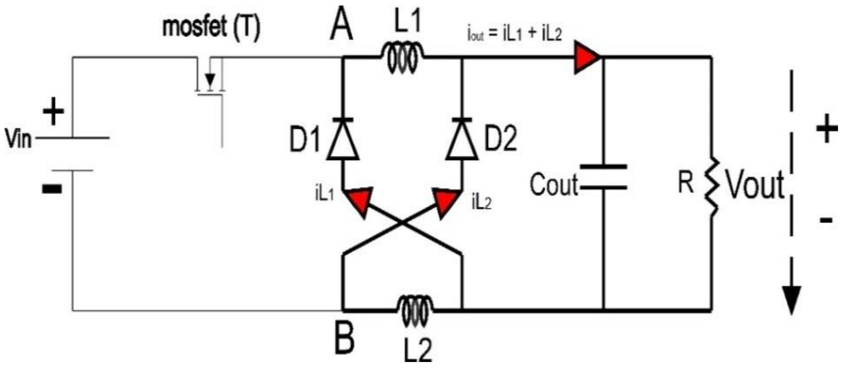


2.8 (a) t_{on} switching topology

$$V_{in} - V_{out} = 2.L.\frac{di_L}{dt} \qquad (2.1)$$

(ii) mode 2

In this working mode the circuit of Buck is shown in figure (2.8.b) the switch mosfet is in open and D1,D2 are in ON state where the inductor L1 and L2 are connected in parallel , and discharge during the period of this mode (t_{off}) .



2.8 (b) t_{off} switching topology.

$$-L.\ \frac{di_L}{dt} = V_{out} \qquad (2.2)$$

The duty Cycle (D) in Continous Condition Mode (CCM) is given below:

$$D = \frac{t_{on}}{T} = \frac{2.V_{out}}{Vin+V_{out}} \qquad (2.3)$$

The ratio of the output to input voltage is given by:

$$\frac{V_{out}}{V_{in}} = \frac{D}{2-D} \qquad (2.4)$$

The voltage of a transistore is as follows:

$$V_T = V_{in} + V_{out} \qquad (2.5)$$

2.5 PID Controller

Several controller techniques have been developed to control the operation of DC-DC converters [32], such as Proportional Integral Derivative (PID), Neural Networks, Fuzzy Controller and Hybrid Control System approaches. The Proportional Integral Derivative (PID) is a type of controller technique that is widely used for regulating and controlling process variables of systems such as position, speed, temperature and pressure, etc. by using control loop feedback. The idea of a PID controller was first introduced in 1911 by the scientist Elmer Sperry and then implemented by Taylor Instrumental Company (TIC) in 1933 [51]. Seven years later, in 1940, the first PID model was developed and then optimized with suitable parameters in 1942 by Ziegler and Nichols. In 1950, the PID controller was extensively used in the industry field [52][53].

Figure 2.9 shows the basic control operations of the PID work in terms of Proportional (P), Integral (I), and Derivative (D). It is accordingly also called Three-Terms Control: the proportional (P) reflects the present state, the integral (I) reflects the past state, and the future state is expressed by the derivative operation (D) [56].

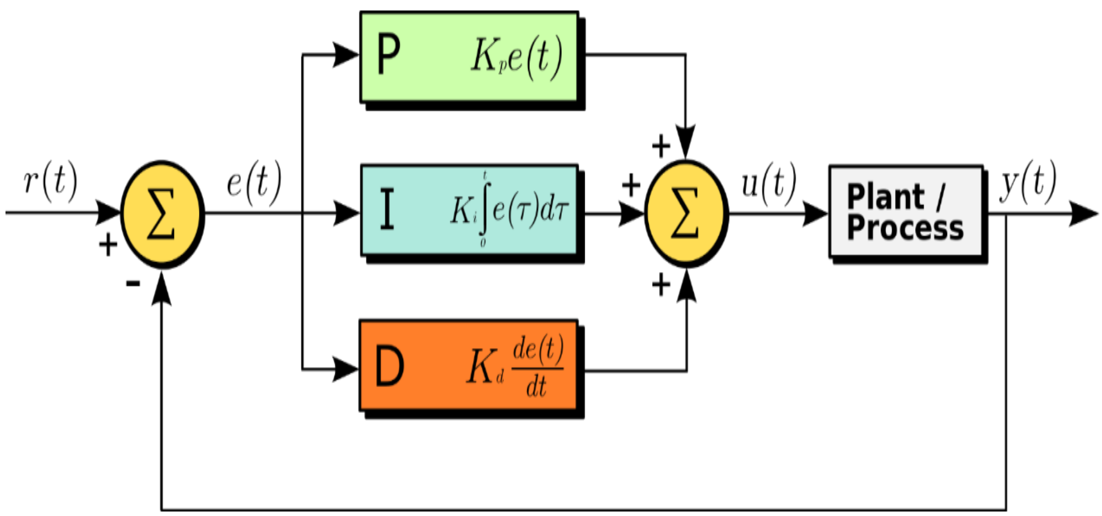


Figure 2.9: A Block diagram in loop feedback for a PID controller.

2.5.1 Tuning process

Generally, the PID controller generates a Control Signal u(t) based on the controlled error signal, which is a difference between the desired signal and actual signal. The command signal *u(t)* is calculated by involving the gain parameters of the PID controller (Proportional, Integral, Derivative), which are relatively independent. The proportional parameter depends on the current error value and the integral parameter deals with the accumulation of past errors,while derivative parameter is a prediction of future errors [56][57].

The PID tries to minimize the error signal as time passes by adjusting the control variable *u(t)*. For instance, flow level control in pipelines system, opening the control valve to an optimum value that is achieved by the weighted sum of the PID terms [57]. The impact of P, I, and D gain parameters can be balanced through loop tuning aiming at obtaining an optimum control function [58]. In the figure 2.9, the tuning constants are referred to by *K*, whose value is derived from the control application used. These constants are mainly used to control the delays and the whole process. Besides, their values can be initially chosen based on the application used but a tuning of these values are performed during the work of the controller. There are several types of tuning methods that can be used by developers to find optimum values for controller parameters and below are some of them [58]:

- Manual: This method can be performed online and does not require mathematical operations, instead, it requires experienced individuals.
- Software: The tuning process is performed by a special-purpose software that can do the task in an automated way (online or offline). However, software tools and training costs are required.

- Cohen-Coon: It needs some math experience and can be performed offline. It is also efficient for the 1st order processes.
- Tyeus Luyben: It can be performed online and used trial and error is required sometimes.
- Astrom-Hagglunk: It can perform auto-tuning and produce efficient outcomes. However, the process is inherently oscillatory.

2.5.2 Control action

The mathematical expression of control action *u(t)* for PID controller in time domain is as follows [59]:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}, \qquad (2.6)$$

Where the tuning parameters K_p, K_i, and K_d are the coefficients for *P*, *I*, and *D* respectively. In fact, there is another form that is widely used instead of (1) as follows [52]:

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int_0^t e(t)dt + T_d \frac{de(t)}{dt} \right), \qquad (2.7)$$

The performance of the PID controller is evaluated based on standard-control-criteria, which are rise time, settling time, maximum overshoot and steady state error parameters.

The PID controller terms have an impact on the response of the Closed-Loop control system as follows:

- **Proportional (*P*):** it can produce a Control Action that is proportional to the present error value. The proportional output can be formalized as follows:

$$P = K_p \; e(t) \qquad (2.8)$$

A high proportional part leads the system to be unstable. While low proportional gain may be small when responding to scheme disturbances.

• **Integral (*I*):** reflects the proportional to the error of both duration and magnitude. It is implemented by multiplying the accumulated error by the integral gain K_i. The accumulated error represents the sum of the Instantaneous Error over time and can be formalized as below:

$$I = K_i \int_0^t \mathrm{e}(\tau)\mathrm{d}\tau \qquad (2.9)$$

The integral part accelerates the movement of the process towards the desired input and eliminates the residual steady state error that occurs with a pure proportional controller. However, it leads the present value to overshoot the demand value.

• **Derivation (*D*):** It can be expressed by multiplying the derivation gain K_d by the error gradient time and can be formalized as the following:

$$D = K_d \frac{de(t)}{dt} \qquad (2.10)$$

The *D* parameter is used to reduce the level of overshoot that is caused by the integral component and enhance the combined controller-process stability. However, the *D* may slow down the transient response of the controller. Besides, the differentiation of a signal amplifies noise and thus this controller part is Highly Sensitive to noise in the error term. This leads a process to become unstable when having sufficiently large derivative gain/noise.

Finally, in most control applications, proper tuning of the PID gain parameters can enable it to provide the system plant by an optimum control signal required to meet the desired output response. Therefore, in this thesis, the PID controller technique is adopted to implement the proposed voltage regulation system for DC-DC Buck converter system.

2.5.3 Applications

The applications of the PID controllers vary from industrial to our daily used devices. It can be said that almost every control process can utilize the PID controllers. Below are some applications that need applying control systems with an accurate control action [60]:

- Heat treatment of metals needs very accurate control to make sure achieving the desired metallurgical features.
- Evaporating solvents from painted surfaces since high temperatures may cause damaged substrates, in addition, low temperatures may also damage the product or produce a poor appearance.
- Curing rubber needs a very accurate control on the temperature aiming at achieving a complete cure with no effects on material properties.
- In baking, commercial ovens should strictly follow specific heating and cooling sequences in order to obtain the required reactions.

2.5.4 PID in Buck converters

PID controller can be used to control the output voltage with what is called Buck convertor [54]. The controller performs a feedback control action in Buck power regulators. The controller generates command signals in form of Pulse Width Modulation (PWM) based on the error signal that is a difference between the reference signal and actual converter signal. A Buck converter is a DC-DC power converter that has three main functions [55];

1) Steps down the voltage to desired output voltage.

2) Stable the output voltage.

3) Buck converter can be used as a quality factor. Moreover, the integration of Buck converters, PID controllers, and bio-inspired computations has been widely used in a variety of applications [54][14][13][12] as presented in this chapter.

2.6 Optimization Methods

Design of power electronic systems have been developed through using intelligent tuning methods that are adopted to optimize the controller performance of these systems. Recently, there is a considerable interest by power electronics engineers on using bio-inspired or nature-inspired approaches on optimization process of power converters. In this thesis, two optimization algorithms namely, Particle Swarm Optimization (PSO) algorithm and Artificial Bee Colony (ABC) algorithm, are used to tune the gain parameters of the feedback control system for Buck converters.

2.6.1 Particle swarm optimization algorithm

The PSO algorithm is a computational approach that, iteratively, can optimize a particular issue aiming at reaching a desirable solution taking into consideration the quality [61]. It is considered a metaheuristic method that is suitable for the optimization of non-linear continuous functions. The basic concept of the PSO method was derived from the principles of swarm intelligence, which can be often observed in animal groups (e.g., bird flocks) [62]. The PSO's first idea was triggered by two scientists Kennedy and Eberhart in 1995 [63]. They tried to produce computational Intelligence through utilizing simple analogs of social interaction instead of the cognitive abilities. This work was influenced by the work of Heppner and Grenander and involved analogs of bird flocks seeking for corn [64]. These intensive experiments led to have a powerful optimization approach called Particle Swarm Optimization.

In the PSO tuning approach, a software agent called Particle to the search space of the problem. The potential optimal solution is characterized or represented by the position of the particle. Hence, each particle in the search space seeks for best positions aiming at having optimal solutions. The change in the position of a particle can be achieved by changing the velocity according to some rules [62].

The steps of implementing the basic version of the PSO algorithm are depicted in the flowchart presented in Figure 2.10 [65]. According to the figure, the initial step is to initialize the population (swarm), which is a group of particles (candidate solutions). Then, it is needed to initialize the best-known positions for the particles. After that, each particle moves in the search space aiming at finding a better position compared to the initial position. Now, when the particle finds the better position, it updates its best position and calculates the velocity accordingly. Then, the algorithm tests the termination criterion whether it is met. These steps are repeated until reaching the termination criterion. In this case, it is not guaranteed to reach a satisfied solution.

The aforementioned description is the basic implementation of the PSO. However, the algorithms can be updated based on the needs and the goals of the implementation. Most of the updates achieved by developers were related to the method of how the velocity is updated for the particles. Hence, many variants of the basic PSO algorithm have been considered in the literature. For instance, the PSO was almost designed to search in domains that are continuous. A discrete version of the PSO was proposed to work in discrete spaces such as the Binary PSO that was proposed by Kennedy and Eberhart in 1997 [66]. This update assumes discrete particle positions and continuous velocity. Another update was introduced by Clerc and Kennedy in 2002 and was called Constriction Coefficient [67]. It assumes that velocity is restricted by a particular form that guaranteed a good update to the velocity. Barebones is another version of the PSO algorithm that was proposed by Kennedy in 2003 [68]. In this variant, the velocity and position of particles are restricted by a particular procedure that, in turn, is based on sampling a parametric PDF (Probability Density Function). The other variant is called Fully Informed PSO, which follows a strategy that allows particles to use information about the neighbors for updating their velocity. This version was proposed in 2004 by Mendes et al. [69]. The literature includes many versions of the PSO that try to obtain better optimization outcomes for control problems.

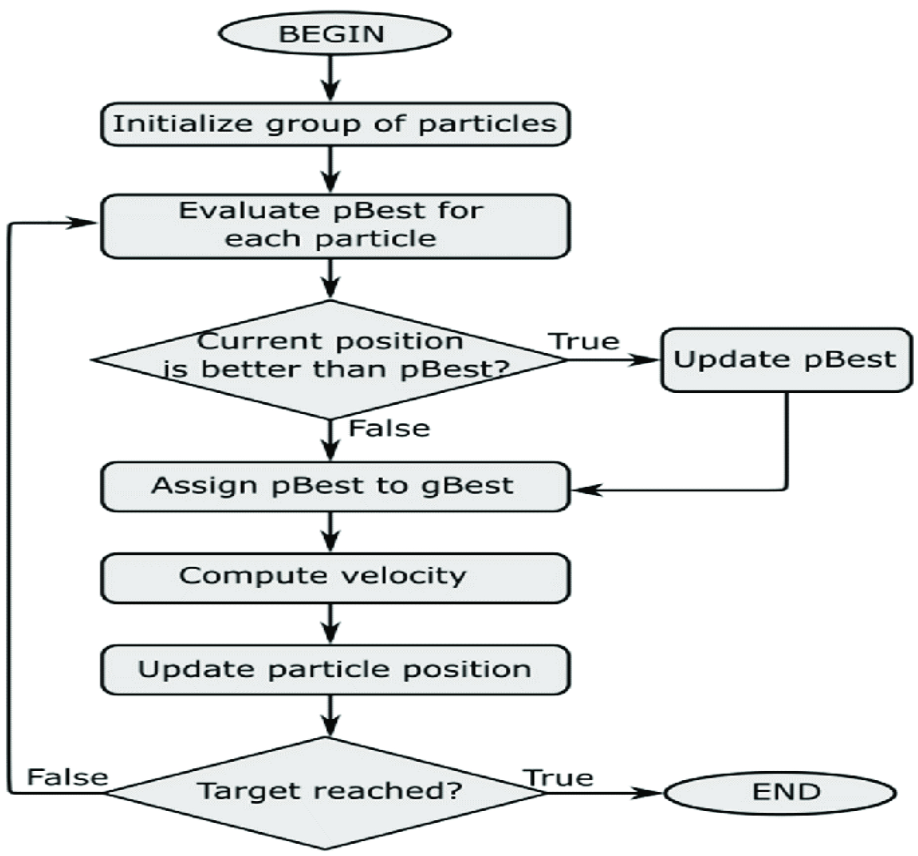


Figure 2.10: Flowchart of the PSO basic step.

Compute velocity through the equation following:

$$V_{i,d}^{t+1} = w^t * V_{i,d}^t + c_1^t * r_1 * (pbest_{i,d}^t - X_{i,d}^t) + c_2^t * r_2 * (gbest_{i,d}^t - X_{i,d}^t) \quad (2.11)$$

And the updated particle position is computed by followig equation .

$$X_{i,d}^{t+1} = X_{i,d}^t + V_{i,d}^{t+1} \quad (2.12)$$

Where denots p = position, g = global position, w = inertia weight, and c = correction factor.

2.6.2 Artificial Bee Colony algorithm

The ABC algorithm is an optimization approach that is inspired by the foraging behavior of bees. It was first introduced in 2005 by the scientist Dervis Karaboga [70]. In the context of bees' colonies, three groups of bees represent the whole community namely, scouts' bees, onlookers' bees, and employed bees. In the latter group, only one bee is assumed for each food source. This means the number of employed bees equals the food sources around the colony's hive. The function of each group can be summarized as follows [70]:

- Employed bees: they go to food sources and come back to their colony's hive. Then they perform specific movements in different directions (e.g., dance-like) aiming at describing the coordinates of a food source.
- Scouts bees: the employed bees whose food source is abandoned becomes scouts. Then, they start seeking new food sources.
- Onlookers bees: This kind of bees interpret the performed movements by the employed bees and then target food sources based on interpretations.

The flowchart shown in figure 2.11 clarifies procedure of optimization process of ABC tuning method. The basic steps of this method are given below [71]:

***Step_1*:** Initial food sources are produced for all employed bees

***Step_2*:** The employed bees go to food sources and detect the closest source. After that, they assess its nectar amount and perform movements in the hive.

using waggle dance equation:

$$v_{ij} = X_{ij} + \beta\ (X_{ij} - X_{kj}) \qquad (2.13)$$

***Step_3*:** The onlooker bees interpret the movements and select one of the food sources according to the interpretation of the movements and go there. Then, they select a neighbor that is around the source aiming at assessing the nectar amount.

***Step_4*:** The abandoned sources are considered as the new food sources. using the following equation

$$X_{ij} = X_{ij} + \text{rand}[0,1](X_{j\max} - X_{j\min}) \qquad (2.14)$$

Where probability equation is given below:

$$P_i = \frac{F(X\text{i})}{\sum_{l=1}^{N} F(X\text{i})} \qquad (2.15)$$

***Step_5*:** The sources in Step_4 are registered.

***Step_5*:** Repeat steps 1 to 5 until the requirements are met.

To apply the ABC in an application, it is needed to interpret each of the concepts mentioned in the above steps to its corresponding optimization concept [72][73][74]. The potential solutions are represented by the positions of food sources. The quality of solutions corresponds to the amount of nectar and the number of solutions equals the number of employed bees.

Now, at the initial step, the initial population (randomly distributed) is generated, which represents food source positions. After that, the search processes cycle of the scouts, onlookers, and employed bees.

Here, the employed bees modify the source position and consider a new source position. Hence, if the amount of nectar of the new source is higher than the previous one, the bee forgets the previous source position and considers the new one. Otherwise, the bee maintains the current considered source position. After completing the search processes by the employed bees, the position information of the sources is shared with the onlooker bees on the movements area (dance area) [73]. Each onlooker assesses the information about nectar is assessed by the onlooker bees, they select the food sources according to the sources amounts of nectar. Repeating these steps will contribute to determining the abandoned sources by the artificial scouts [74].

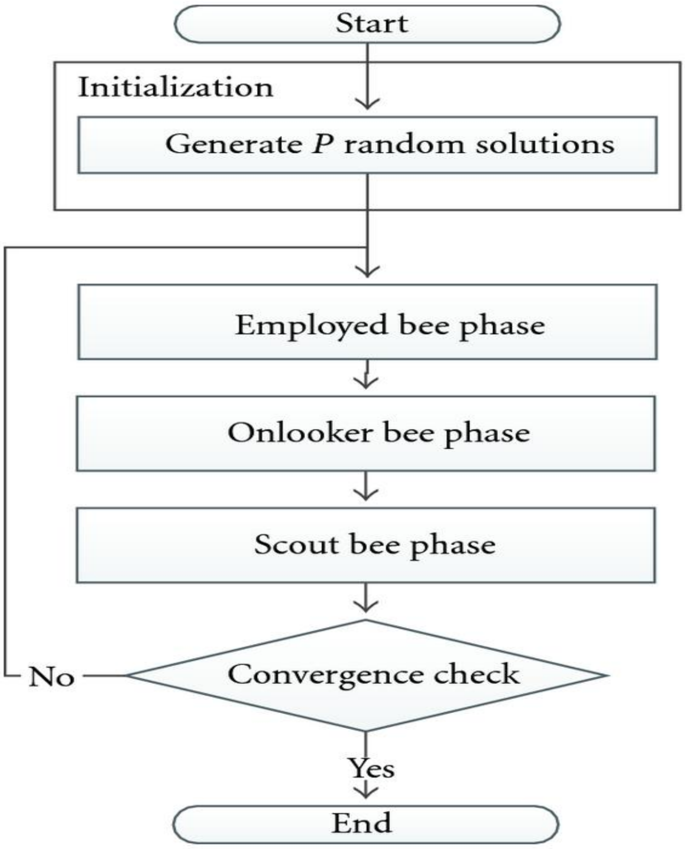


Figure 2.11: Flowchart of the ABC algorithm basic steps.

It is worth considering that, the simplicity of the ABC algorithm attracted attention of many researchers around the world to use this algorithm for optimizing their problems or tuning their models' parameters [75]. Also, the ABC algorithm is considered a global numerical optimization algorithm that can be used for constrained and unconstrained problems using only three parameters (e.g., max number of cycles, limit, and population size). These three parameters can be predetermined by developers or users.

The ABC algorithm has a wide range of applications in the fields of electrical engineering, power electronics, computer engineering, etc. In addition, it can be adopted in cluster analysis, structure prediction, training neural networks, and forecasting applications [76]. The recent trends in using the ABC algorithm are in numerical problems such that optimizing complicated benchmark test functions in large scales [77].

Chapter Three
Modeling of A Buck Converter

3.1 Overview

Buck converters or called step-down converters are considered DC-DC switch-mode power supply devices. The main purpose of this type of converters is to lower or Buck the input DC voltage to a stable lower output DC voltage [34]. A Buck converter model includes a resistor, inductor, capacitor, diode and transistor. The feedback signals in form of Pulse Width Module (PWM) are used to control the switching process of a Buck converter. Figure 3.1 depicts a classic Buck converter circuit diagram.

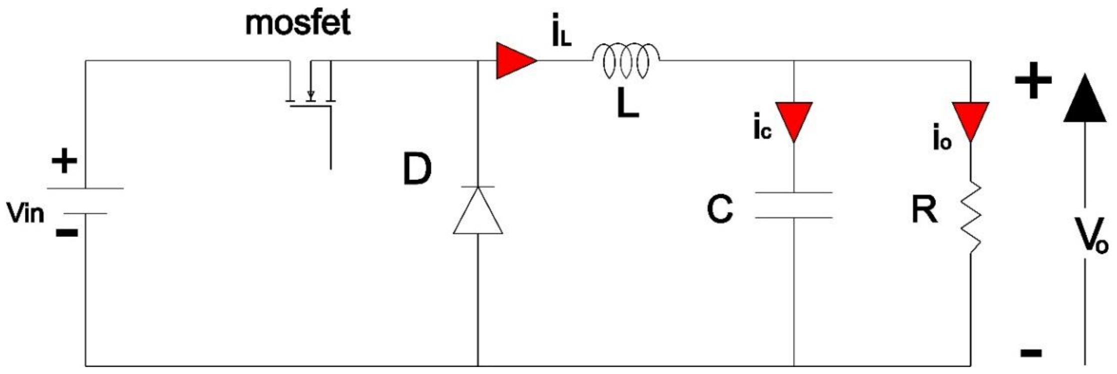


Figure 3.1: A classic circuit diagram of a Buck converter.

To analyze the above converter electric circuit, it is required to describe its components.

- **Load:** It is any appliance that is connected across the output terminals of the converter. It can be a simple resistive or complex resistive with passive and active elements.
- **Capacitor:** it performs a filter stage in converter circuit, which is needed for the output voltage waveform to be smoothened. It is also able to filter the rippled waveform and provide a constant

output voltage across the load.

- **Inductor:** It is a power storage unit in the converter system. It reduces the current ripple and make it smoother. It is also used to decrease the high values of d_i/d_t that are caused at switching process. In addition, it is used to improve the regulation process of the converter output voltage, this process is considered crucial during the switching flow in current that leads to protect the switch when it is under stressed.
- **Diode:** It is needed to provide a path for the inductor current to flow through the load as soon as the switch is OFF [34][41].
- **MOSFET Switch:** In case of the input voltage (V_{in}) to the gate of the transistor is zero, MOSFET conducts virtually no current and the output voltage (V_{out}) is equal to the supply voltage.

According to the above figure, the behavior of the Buck converter depends on two states of switching [34]. In the first one, the switch is ON connected to i_L making a charging status. While, the second one is discharging status when the switch is OFF.

This chapter presents model of the Buck converter system in two switching modes and averaging them according to the duty cycle. In case of having a high frequency of switching, the L filter will not be able to manage the individual switching events due to the existence of high frequencies [34][41]. Therefore, the Switching frequency is selected to be 100kHz and the interval of the sampling is set to 10 μs, hence, with the PWM control, the regulation of V_{out} is achieved by changing the Duty cycle of the device switch and at the same time maintaining a constant level of operation frequency that can be managed [78]. The term Duty cycle reflects the ratio of the period of the circuit's source voltage, to the total cycle period. In case the level of controller output $u(t)$ is relatively greater than the repetitive saw-tooth waveform, the switch is connected to i_L and the input voltage is considered to be the source. Otherwise, OFF state will be the status of the switch and the applied voltage to the converter circuit from the source is 0V.

The frequency of the repetitive waveform with a constant peak (saw-tooth) initiates the frequency of switching, which is maintained constant in the PWM [78].

3.2 Buck Converter Working Modes

There are two modes of operations in Buck converters, discrete and continuous. In the former, a period is existed and the current of the inductor $i_L(t)$ is interrupted. While, in continuous mode no period is existed and the current of the inductor $i_L(t)$ is zero. The detail of these two working modes are presented in detail in the following subsections.

3.2.1 Discrete Condition Mode (DCM)

In this working mode, there is a zero-inductor current period between the ON and OFF switching operations [79]. Therefore, the inductor current is not continuous. The size and cost of the discrete mode are reduced compared to the continuous mode [80]. The discrete mode has a fast recovering of the rectifying diode and high allowable power for the switching transistor. The discrete condition mode is not the concern in this thesis because the proposed converter approach is based on the continuous condition mode.

3.2.2 Continuous Conduction Mode (CCM)

In continuous working mode, the current of the inductor flows continuously during the switching period (T). During this mode, a priority for reducing the output ripple voltage and harmonics is considered [81][82]. The operation of the Buck converter bases on the switching function. Therefore, based on the switch state, two electric circuits are considered, one for the ON state and other for the OFF state. The CCM waveform is shown in Figure 3.2 and the equations are given below:

$$x=[A_1d+A_2(1-d)]x + [B_1d+B_2(1-d)]v_{in} \tag{3.1}$$

$$v_0=[C_1d+C_2(1-d)]x \tag{3.2}$$

where d = the time during the switch is ON.

(1-d)= the time during the switch is OFF.

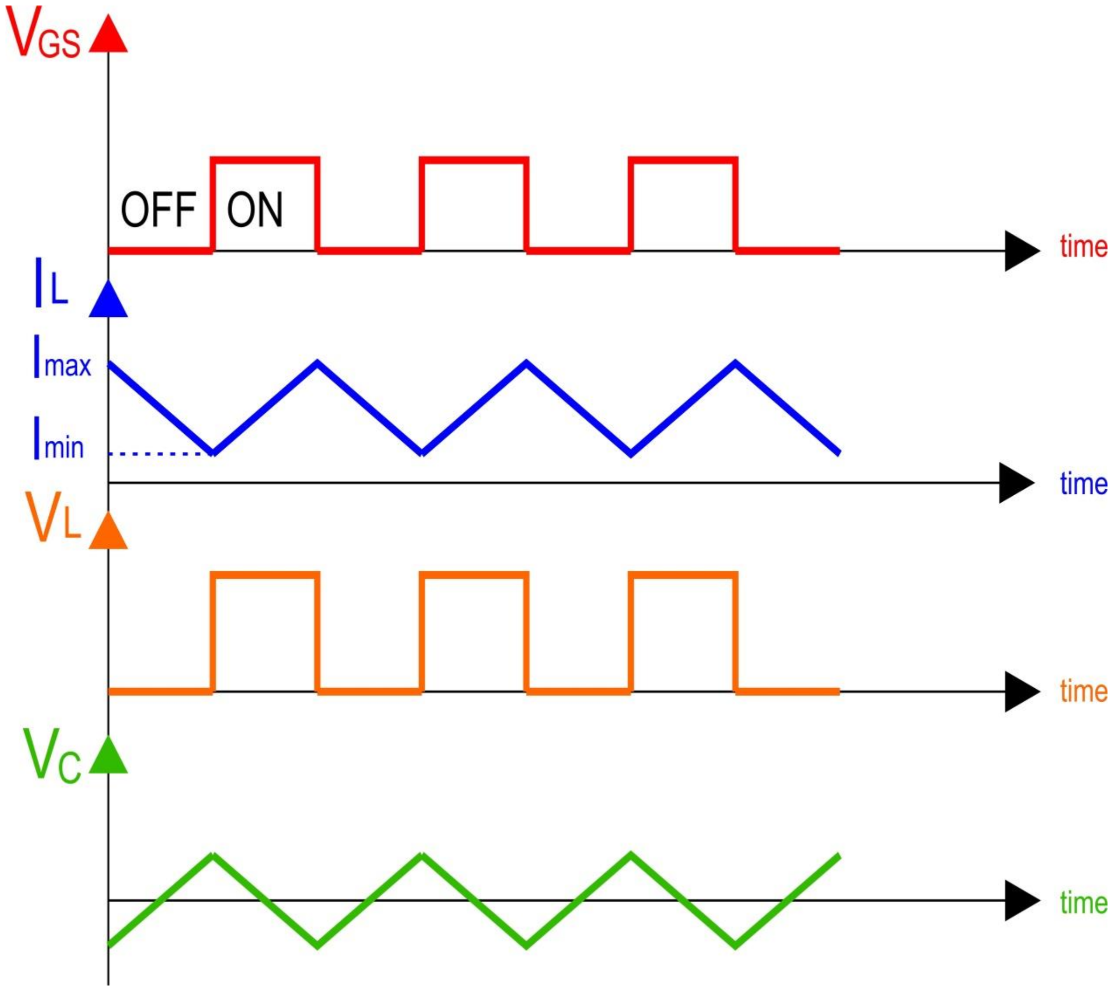


Figure 3.2: Continuous Conduction Mode (CCM) Waveforms

3.3 Buck Converters Switching Modes

Buck converters work in two switching modes as described in the following subsections.

3.3.1 Switch ON state

In this working state, the switch is connected to ON state and the voltage source $V_s(t)$ is included to the converter circuit. Figure 3.3 demonstrates a Buck converter diagram in case the switch status is ON. Under this state, a reverse current is occurred during the Reverse Recovery Time of the diode, which causes a loss as a side effect of the ON state as well as the time consumed in the reverse recovery [81]. In low-voltage switching, the Reverse Voltage and Reverse Current of the diode are low [83].

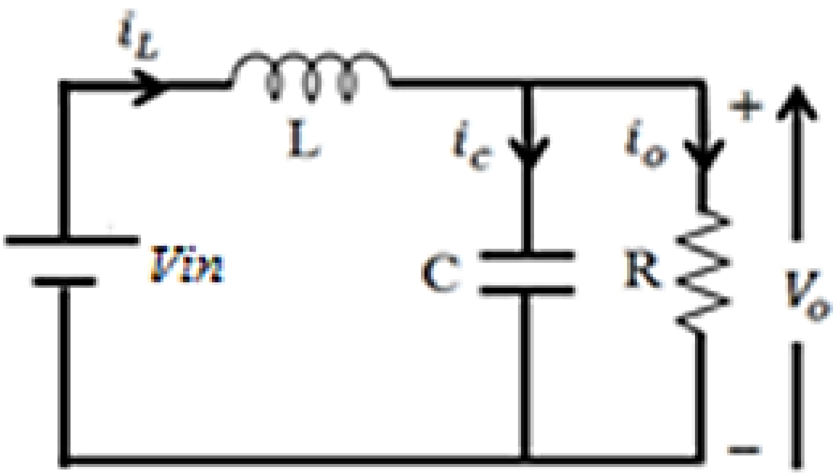


Fig. 3.3 Buck converter switch ON state.

.

During this working case, the diode is Reverse Biased and the load is connected to the supply voltage through the inductor in a direct way. The inductor current flows through the switch and the voltage of the inductor can be as follows:

$$L\frac{di_L(t)}{dt} = V_{in} - V_o \tag{3.3}$$

while the capacitor current is as follows:

$$C\frac{dV_c(t)}{dt} = i_L(t) - i_o(t) \tag{3.4}$$

The State Variables of the system are the voltage of capacitor and the current of the inductor. The state vector $x(t) = [x_1(t) \quad x_2(t)]^T = [i_L(t) \quad V_c(t)]^T$. The applied voltage to the Buck converter is considered the control input's vector such that, $u(t) = V_{in}(t)$. In state space formulation of the Buck converter, the inductor current, $i_L(t)$ and capacitor voltage $V_c(t)$ are chosen as the state variables, $V_s(t)$ is chosen as an input signal, while $V_c(t)$ as the output signal. Based on Equations 3.3 and 3.4, the state space formulation of the converter system is represented by the following state and output equations.

$$\begin{bmatrix} \dot{i}_L(t) \\ \dot{V}_c(t) \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & \frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in}(t) \tag{3.5}$$

$$y(t) = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} \tag{3.6}$$

$$\dot{x}(t) = A_1 x(t) + B_1 u(t) \tag{3.7}$$

$$y(t) = Cx(t) \tag{3.8}$$

Where the state matrix $A_1 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & \frac{1}{RC} \end{bmatrix}$, the input matrix $B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}$ and the output matrix $C_1 = [0 \quad 1]$.

3.3.2 Switch OFF state

During the OFF state of the switch, the freewheeling diode gets ON and provides a path to dissipate the energy stored in the inductor via the resistor of the load. The schematic diagram of corresponding sub-circuit of Buck converter is shown in Figure 3.4. In this working mode, $d \prec t_{off} \prec T$, using Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL), the voltage of the capacitor and the current of the inductor in the converter system are provided in Equations 3.9 and 3.10 respectively [83].

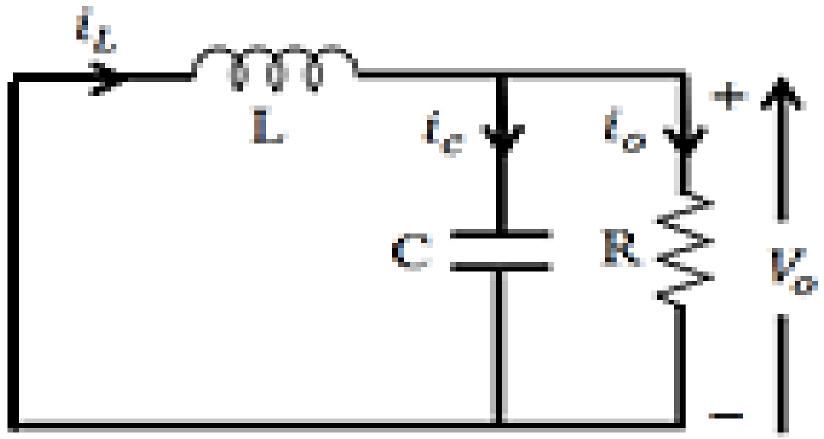


Fig. 3.4 Buck converter switch OFF state.

$$\frac{di_L(t)}{dt} = \frac{V_c(t)}{L} \tag{3.9}$$

$$\frac{dV_c(t)}{dt} = \frac{i_L(t)}{C} - \frac{V_C(t)}{RC} \tag{3.10}$$

The state and output equations of the Buck converter system based on switch OFF state are given in Equations 3.11 and 3.12 respectively.

$$\begin{bmatrix} \dot{i}_L(t) \\ \dot{V}_c(t) \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & \frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in}(t) \qquad (3.11)$$

$$y(t) = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L(t) \\ V_c(t) \end{bmatrix} \qquad (3.12)$$

$$\dot{x}(t) = A_2 x(t) + B_2 u(t) \qquad (3.13)$$

$$y(t) = C_2 x(t) \qquad (3.14)$$

Where $A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & \frac{1}{RC} \end{bmatrix}$, $B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$ and $C_2 = \begin{bmatrix} 0 & 1 \end{bmatrix}$.

To derive an average model of the power converter system over one switching cycle, the following techniques are used:

1- Averaging the circuit: it is an opposed to equation averaging and it is a common approach for circuit simulations. It can also be applied by separating the switch from the remainder of the converter, then, define ports of the switch. After that, it is needed to average the switch waveforms.

2- Averaging the state space: it means dividing the switching circuit into two or three structures. The derivatives of the inductor currents and capacitor voltages are defined for each structure. The voltages and currents are averaged over one switching cycle.

3- PWM switch modeling: it is a simple continuous state-space method that uses currents and voltage sources for controlling DC-DC convertors, which is different from the first mentioned technique.

The state space averaging has advantages compared to the first techniques. For instance, the second technique has a more compact representation of equations as well as its ability to obtain more transfer functions. Also, in the state-space, both AC and DC transfer functions can be easily obtained. Based on the aforementioned advantages, this thesis utilizes the state-space approach.

In this thesis, the model of the system is formed by state-space averaging technique. The state space representation of the Buck converter model can be formulated using state space averaging approach by multiplying the Equations 3.7, 3.8 by d and Equations 3.13, 3.14 by $(1-d)$ and the resulting equations are added together. The resulting general state and output equations of the converter model are given in Equations 3.15 and 3.16 respectively:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{3.15}$$

$$y(t) = Cx(t) \tag{3.16}$$

where $A = A_1 d + (1-d)A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, B = B_1 d + (1-d)B_2 = \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix},$

$$C = C_1 d + (1-d)C_2 = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

Taking the Laplace transform of Equation 3.15, the transfer function of the DC-DC Buck converter system with respect to supply voltage is given by Equations 3.17.

$$\frac{V_o(s)}{V_{in}(s)} = C(sI - A)^{-1} B + D \tag{3.17}$$

Based on the Equations 3.15 and 3.16, the transfer function equation of the converter system (Equations 3.17) is expressed as follows:

$$\frac{V_o(s)}{V_{in}(s)} = \frac{\frac{d}{LC}}{s^2 + \frac{1}{RC}s + \frac{1}{LC}} \tag{3.18a}$$

$$\frac{V_o(s)}{d} = \frac{\frac{V_{in}(s)}{LC}}{s^2 + \frac{1}{RC}s + \frac{1}{LC}} \tag{3.18b}$$

In Steady State, the average capacitor current is assigned to be Zero, the current of the inductor is equal to the output current of the converter $(i_L(t) = i_o(t))$.

$$(V_{in}(t) - V_o(t))t_{on} = V_o(t)(T_s - T_{on}) \tag{3.19}$$

Based on the above equation, the duty cycle($\acute{D}$) is formalized as follows:

$$\acute{D} = \frac{T_{on}}{T} \tag{3.20}$$

Chapter Four

Classic and Hybrid Buck Converter Simulations

4.1 Classic Buck Converter Simulation

The design of Buck converter control system was simulated using Matlab environment aiming to validate the proposed PID controller. In this thesis, Matlab script was used to implement two optimization techniques namely, PSO and ABC, which are adopted to find the best values for PID parameters. The regulation system of the Buck converter was simulated using Matlab Simulink software to validate the optimized PID controller.

The simulation parameters are listed in table 4.1 these parameters will be used in designing and simulation of the Buck converter.

Table 4.1: Buck converter calculated parameters.

Parameters	Value
Input voltage (Vin)	24 v
Output voltage (Vo)	6 v
Resistore (R)	10 Ω
Frequency Switching (f_S)	100 KHz
Peak to peak output ripple voltage (△Vc)	0.3 v
Peak to peak ripple current (△I)	30 mA

Based on the parameters listed in the table 4.1, the Buck circuit elements are determined as follows:

L=1.875×10^{-4} H, C=1.25×10^{-7} F.

4.1.1 Classic Buck converter simulation based on PSO algorithm

In this section, four working cases are considered, which will be taken in detail, to verify the robustness of the proposed PID feedback control system for Buck converter. The model of the Buck voltage regulator is simulated using Matlab/ simulink tool. It is worth considering that most of the model components for the converter plant are inserted from simulink power systems library, while the variable resistor is included from simulink simscape electrical components library.

Based on the PSO tuning method, the optimized PID controller parameters are given below:

K_p= 95.497, K_i=0.0159 and K_d=0.0048

PSO-case I: Steady state

In this working case, the Buck converter system based on PSO-PID controller is simulated using electric components with constant values with time. The simulink model of the voltage controlled Buck converter system is shown in Figure 4.1. The parameters values of the model are listed in Table 4.2. Based on the Matlab command sim a connection between the Matlab script file, which is used to implement the PSO tuning algorithm for PID controller parameters, and simulink model of the converter is achieved.

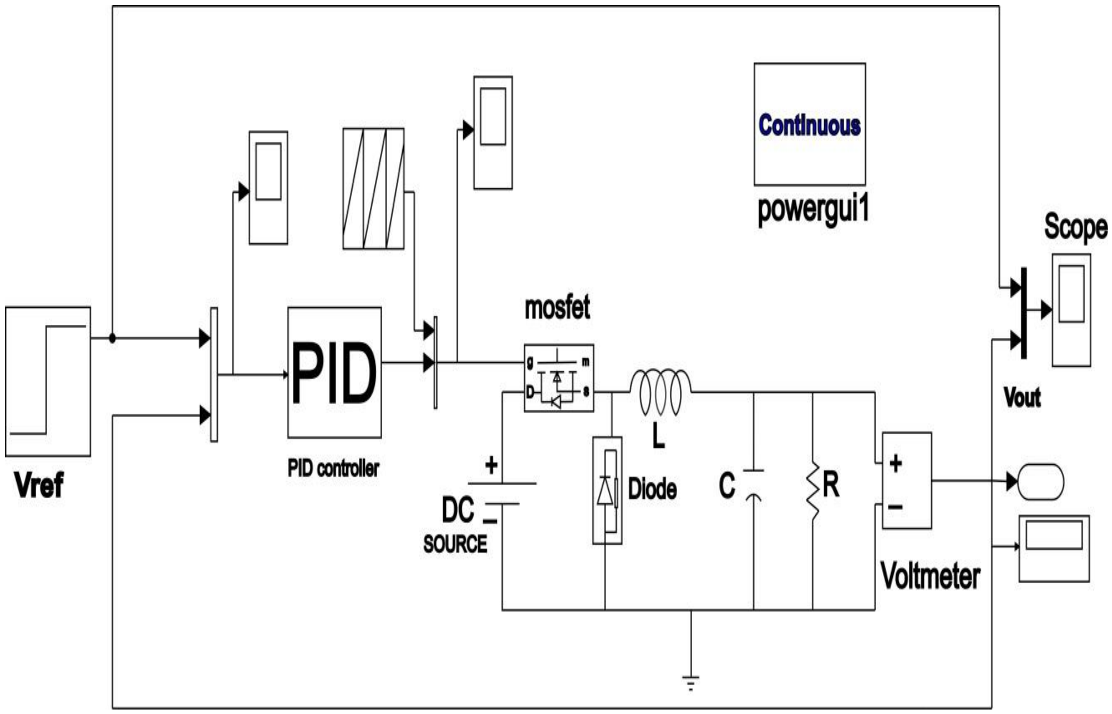


Figure 4.1: Simulink model of PSO-PID for PSO-case I.

Table 4.2: Buck converter parameters for PSO-case I.

Parameter	Symbol	Value
Input voltage	V_{in}	24 v
Reference voltage	V_{ref}	6 v
Inductance	L	1.875×10^{-4}H
Resistance	R	10Ω
Capacitance	C	1.25×10^{-7}F

Table 4.3 PSO algorithm parameters

Parameter	Symbol	Value
Population size		20
No. of iterations	N	20
Congitive component	C_1	1.6
Social component	C_2	1.6
Max. speed	C	10
Max inertia weight	w_{max}	0.9
Min. Inertia weight	w_{min}	0.4

The optimization process using PSO algorithm is implemented based on the algorithm parameters listed in Table 4.3. Based on the optimized PID gain parameters, the output voltage of the Buck converter based on PSO algorithm is shown in Figure 4.2. It is clear from the mini-plot of the figure, that the optimized feedback PID control system succeeded to guide the Buck converter output voltage through the desired reference trajectory effectively.

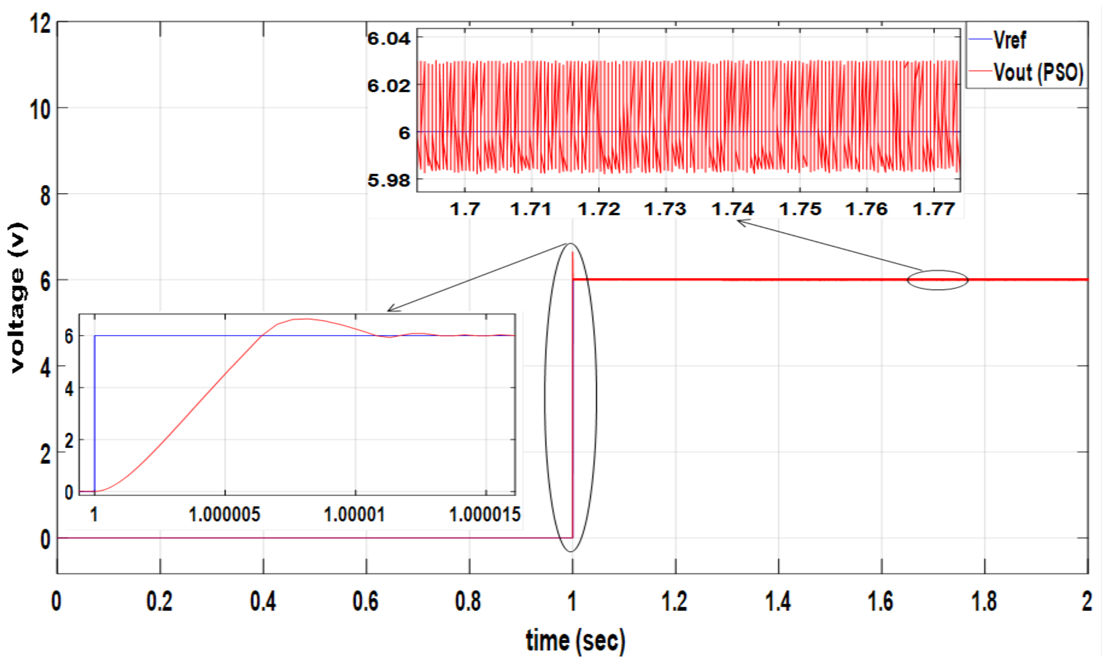


Figure 4.2: The response of the model without disturbance for PSO-PID simulation result.

Table 4.4 illustrates the output characteristics of the Buck converter based on the simulation result in figure 4.2.

Table 4.4: The system characteristics for PSO case-I

Parameters	Value
Average overshoot	10.834%
Rise time (us)	5
Settling time (us)	20
Steady state error (v)	0.03
Peak to peak output ripple voltage ($\triangle$V)	0.206%

PSO-case II: Source voltage disturbance

In the present case, the conversion performance of the Buck regulator system is investigated based on a sudden change in the converter source voltage. The Buck converter cicuit is supplied by a sequential repeated values source voltage. Figure 4.3 shows the simulink schematic diagram of the Buck converter based on PSO-Case II using the circuit parameters presented in Table 4.5.

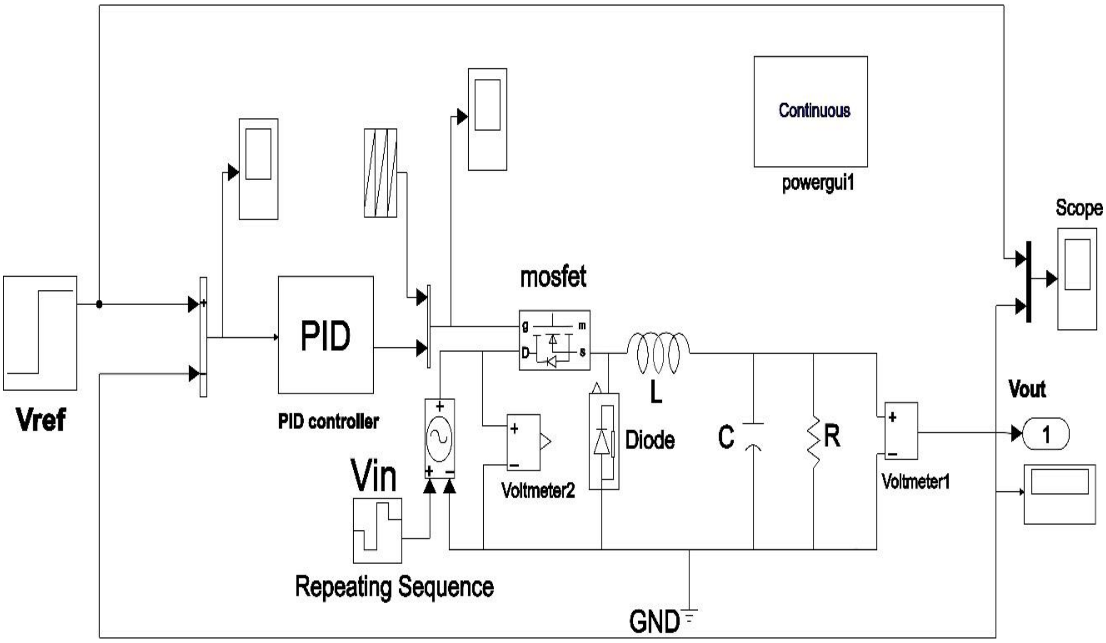


Figure 4.3: The simulink model of PSO-case II using repeated values source voltage.

Table 4.5: PSO-Case II parameters using sequential repeated values source voltage.

Parameter	Symbol	Value
Input voltage	V_{in}	[10 25 15 20]V
Reference voltage	V_{ref}	6 v
Inductance	L	1.875×10^{-4}H
Resistance	R	10Ω
Capacitance	C	1.25×10^{-7}F

The response of the Buck converter system is shown in Figure 4.4. It can be noted from the miniplot of Figure 4.4 that, the Buck converter under action of the optimized PSO-PID controller efficiently provided quick and fast responses, and delivering a stable output voltage with minimal error steady state.

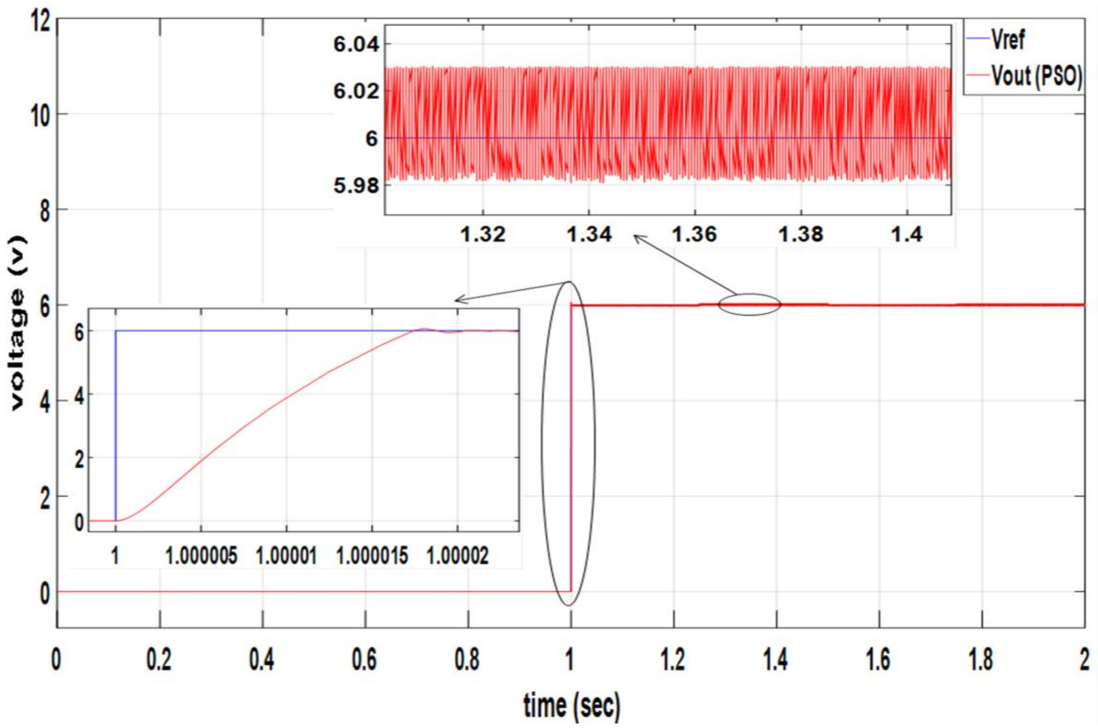


Figure 4.4: Response of PSO-PID controller using variable source voltage.

The following Table 4.6 illustrates the system characteristics based on the simulation result in figure 4.4.

Table 4.6: The system characteristics for PSO case-II

Parameters	Value
Average overshoot	1.0166%
Rise time (us)	14.5
Settling time (us)	23
Steady state error (v)	0.0295
Peak to peak output ripple voltage ($\triangle$V)	0.318%

PSO-case III: Reference voltage disturbance

In this case, the regulation performance of the Buck converter is evaluated based on the parameters presented in Table 4.7 using the PSO-PID approach. The simulink diagram of the Buck converter system based on a triangle reference voltage is depicted in Figure 4.5.

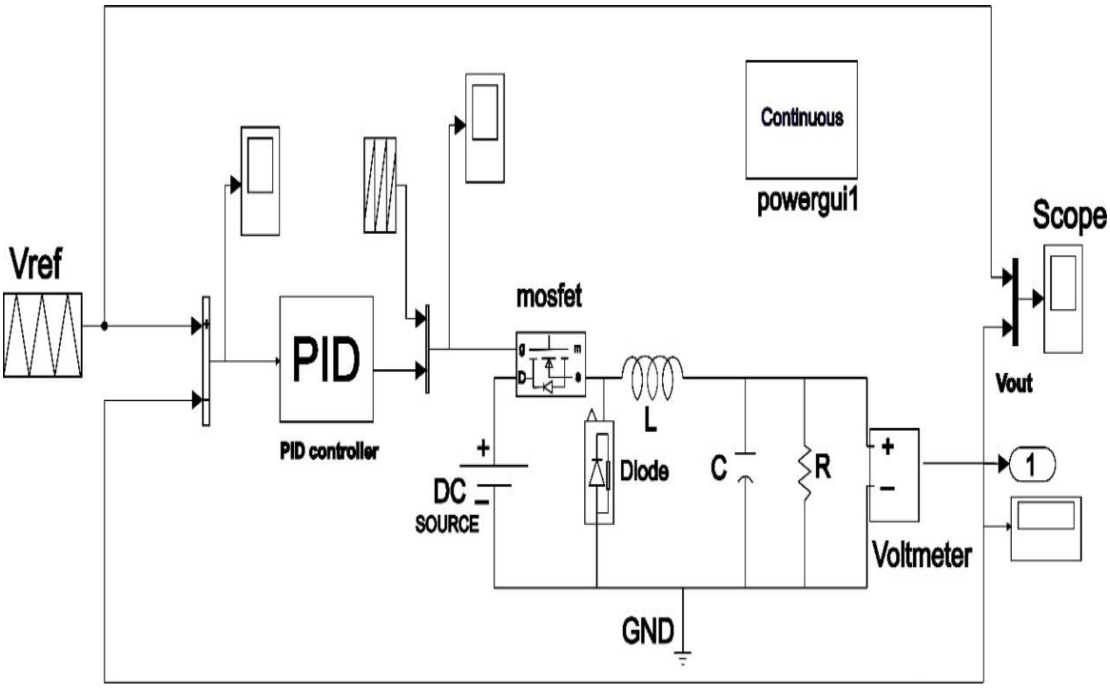


Figure 4.5: Simulink model of PSO-case III using triangle reference voltage.

Table 4.7: Electric parameters of Buck converter based on PSO-case III.

Parameter	Symbol	Value
Input voltage	V_{in}	24
Reference voltage	V_{ref}	[0 6 0]v
Inductance	L	1.875×10^{-4}H
Resistance	R	10Ω
Capacitance	C	1.25×10^{-7}F

Figure 4.6 including its mini-plot shows the response of the Buck converter based on triangle desired voltage. It is obvious from the output response that the output voltage of the Buck converter followed the demand input voltage trajectory efficiently with fast rise and settling times .

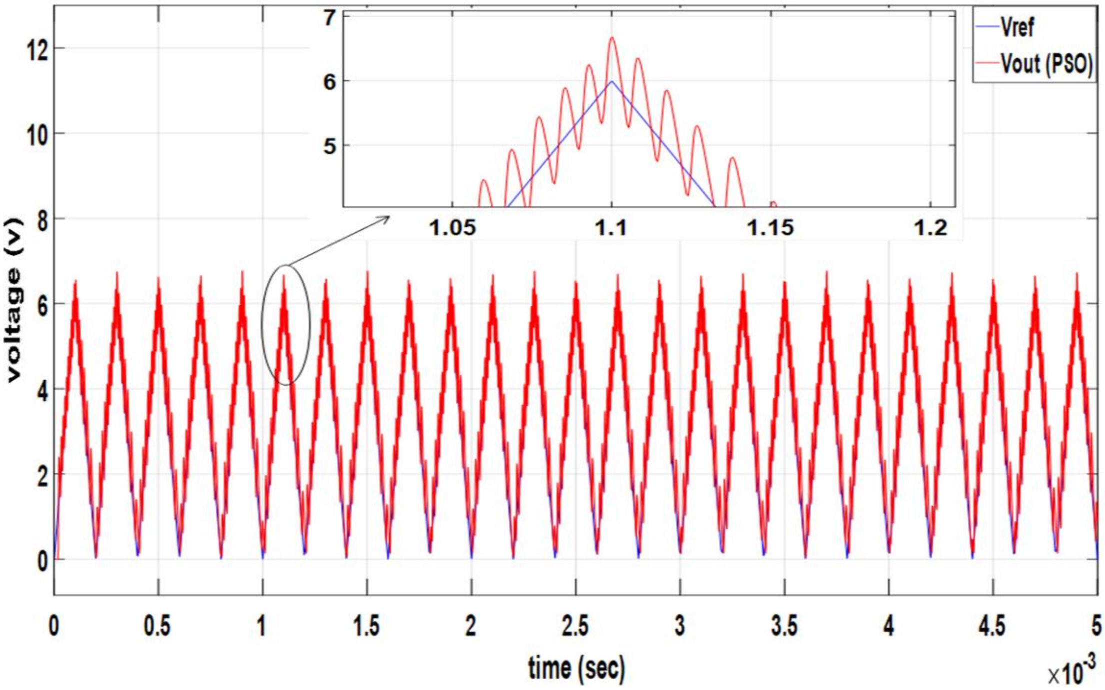


Figure 4.6: Response of PSO-PID controller under reference voltage disturbance.

Based on the simulation result of the system shown in figure 4.6, Table 4.8 shows the characteristics parameters of the converter output.

Table 4.8: The system characteristics for PSO-case III

Parameters	Value
Average overshoot	11.263%
Steady state error (v)	0.675
Peak to peak output ripple voltage (△V)	4.596%

PSO-case IV: Source, reference and load disturbance

In this working case, three categories of uncertainties, variation in supply voltage, desired reference voltage and load resistance are considered in the converter model to varify the robustness of the proposed PID controller. Table 4.9 presents the converter parameters in this working case. The simulink diagram of the Buck converter is depicted in Figure 4.7.

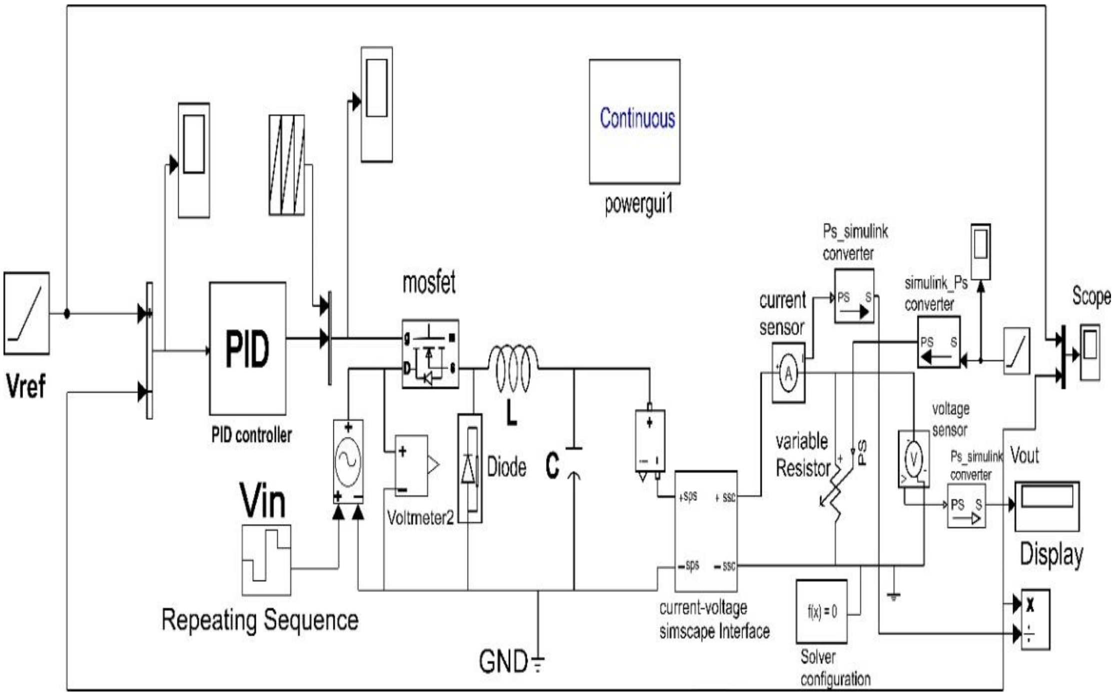


Figure 4.7: The simulink model of PSO-case IV

Table 4.9: PSO-case IV parameters.

Parameter	Symbol	Value
Input voltage	V_{in}	[10 25 15 20] v
Reference voltage	V_{ref}	0-5v
Inductance	L	1.875×10^{-4}H
Resistance	R	1-5Ω
Capacitance	C	1.25×10^{-7}F

The output response of the Buck convert under variation in the source voltage, desired voltage and load resistance is presented in Figure 4.8. It can be seen from the system output response that the voltage controlled Buck converter using an optimized PSO-PID controller followed the demand variable reference input trajectory efficiently .

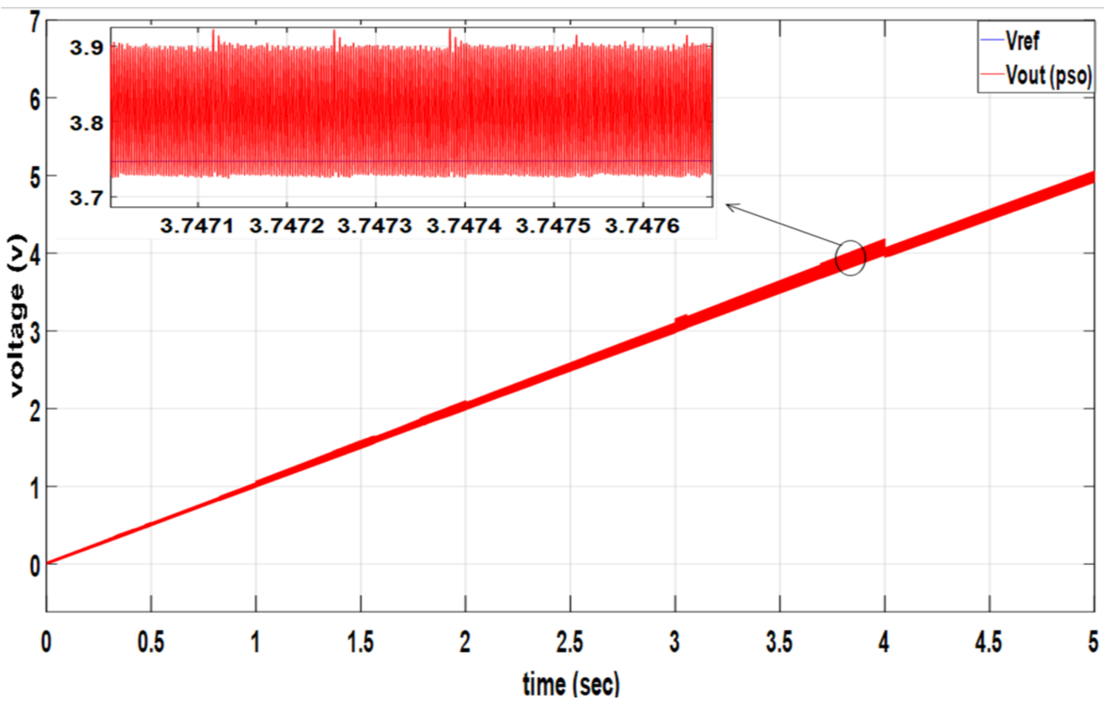


Figure 4.8: Response of PSO-PID based Buck converter under disturbance in supply votage, desired voltage and load resistance.

Based on the simulation result of the system shown in figure 4.8, Table 4.10 present characteristics parameters of the converter output response.

Table 4.10: The system characteristics for PSO case-IV

Parameters	Value
Steady state error (v)	0.1506
Peak to peak output ripple voltage ($\triangle V$)	2.155%

4.1.2 Classic Buck converter simulation based on ABC algorithm

This section follows the same structure of the previous section in terms of the cases considered in this thesis. four working cases are considered, which will be taken in detail, to verify the proposed PID feedback control system for Buck converter under the ABC algorithm. The model of the Buck voltage regulator is simulated using Matlab/ Simulink tool to evaluate the proposed ABC-PID controller.

After applying ABC optimization algorithm the tuned PID controller parameters are given below:

K_p= 507 ,K_i=63.9017, K_d=0.308

ABC-case I: Steady state

In this case, fixed values for the Buck converter parameters were used in the system simulation. The simulink model of the Buck converter is the same as that of PSO based Buck converter as previously shown in Figure 4.1.

Table 4.11 ABC algorithm parameters

Parameter	Value
Colony size	40
Onlooker bees	20
Employed bees	20
Limit	30
Number of cycles	100

The optimization process using ABC algorithm is implemented based on the algorithm parameters listed in Table 4.11.

The output response of the Buck converter based on fixed circuit parameters values using ABC-PID is demonstrated in Figure 4.9. From figure 4.9 it is obvious that, the Buck converter achieved fast response, and delivered a stable output voltage efficiently with minimal error steady state.

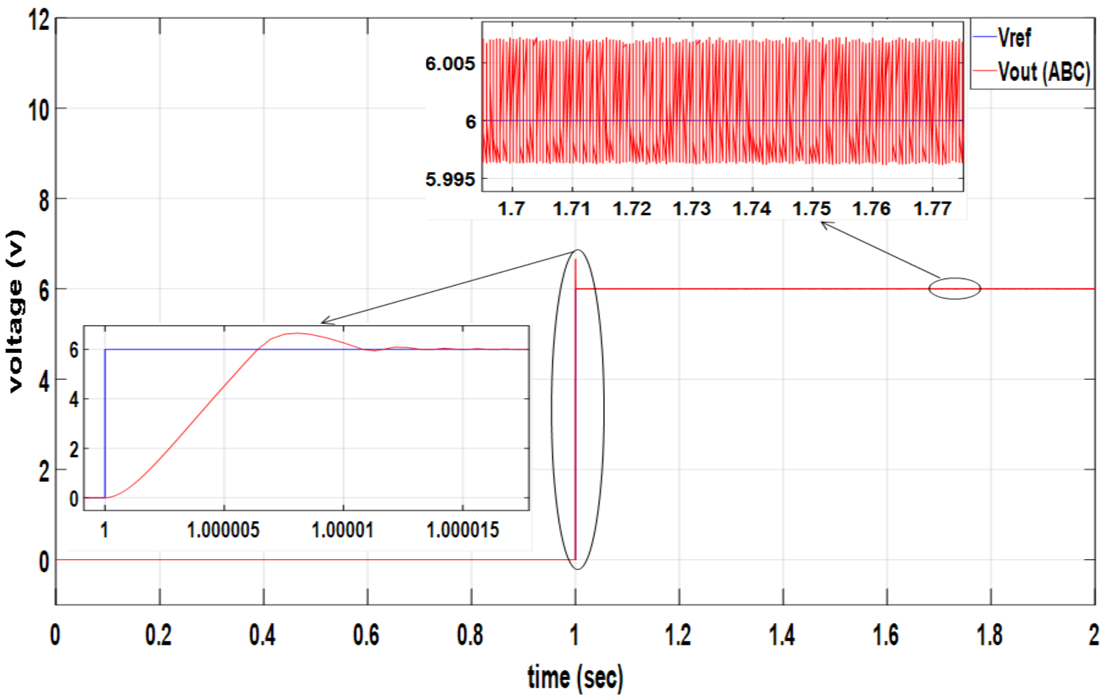


Figure 4.9: The response of model without disturbances for ABC-PID simulation result.

Based on the simulation result of the system shown in figure 4.9, Table 4.12 presents characteristics parameters of the converter output response.

Table 4.12: The system characteristics for ABC-case I

Parameters	Value
Average overshoot	10.86%
Rise time (us)	4
Settling time (us)	18
Steady state error (v)	0.007
Peak to peak output ripple voltage ($\triangle$V)	0.058%

ABC-case II: Source voltage disturbance

In this case, the conversion performance of the Buck regulator system is investigated based on a sudden change in the converter source voltage. The simulink model of the ABC-PID based converter system is the same simulink schematic of PSO-PID system as previously shown in Figure 4. 3.

The output response of simulating ABC-Case II is depicted in Figure 4.10. It can be observed from the system output that the Buck converter under action of the ABC-PID controller achieved a fast transient response, and delivered a stable output voltage efficiently with minimal error steady state using the aforementioned parameters.

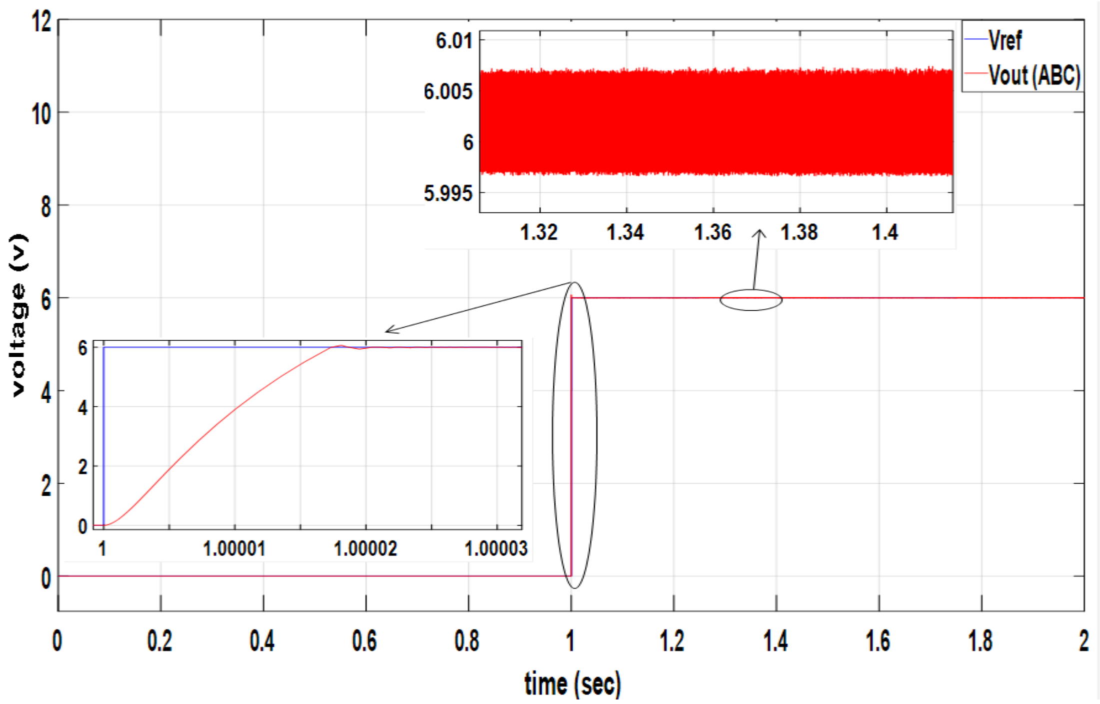


Figure 4.10: The response of source voltage disturbance for ABC-PID simulation result

Table 4.13 illustrates the output characteristics of the Buck converter result in figure 4.10.

Table 4.13: The system characteristics for ABC case-II

Parameters	Value
Average overshoot	1.065%
Rise time (us)	13
Settling time (us)	25
Steady state error (v)	0.006
Peak to peak output ripple voltage (ΔV)	0.064%

ABC-case III: Reference voltage disturbance

In the present case, the regulation performance of the Buck converter is evaluated based on triangle reference voltage. The simulink model of the system is the same simulink diagram of PSO-PID based converter system as previously presented in Figure (4.5)

Figure 4.11 demonstrated that the output voltage of the Buck converter based on ABC-PID controller. From the minifigure of the system response, it is clear that the controller forced the converter output to follow the desired input trajectory efficiently, where, the transient response of the captured voltage signal is fast .

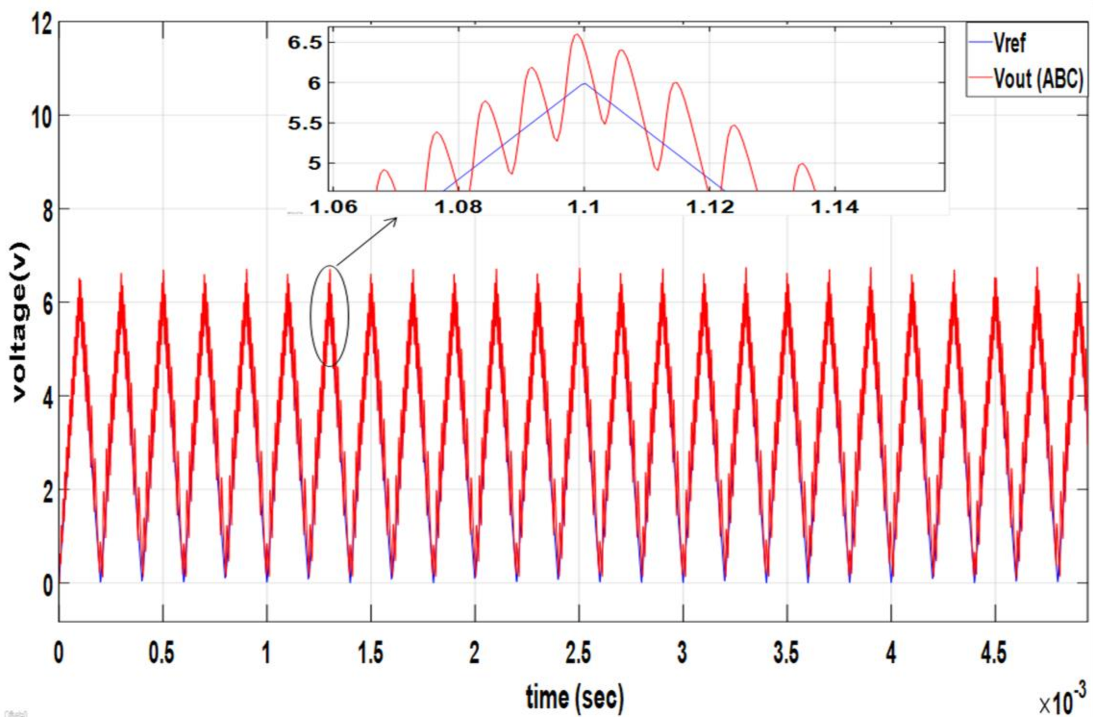


Figure 4.11: The response ABC-PID based Buck converter system based on varying reference voltage.

Table 4.14 illustrates the output characteristics of the Buck converter based on the simulation result in figure 4.11.

Table 4.14: The system characteristics for ABC case-III

Parameters	Value
Avgerage overshoot	10.033%
Steady state error (v)	0.602
Peak to peak output ripple voltage ($\triangle$V)	4.2%

ABC-case IV: Source, reference and load disturbance

In this working case, three categories of uncertainties, variation in supply voltage, desired reference voltage and load resistance are considered in the converter model and its voltage regulation behaviour is examined in order to validate the effectiveness of the proposed PID controller. The simulink model of the converter system is the same model of PSO-PID based converter system as previously presented in Figure 4.7.

The adjustment performance of the Buck converter using ABC-PID controller is shown in Figure 4.12. This figure reveals that, the Buck converter based on an optimized ABC-PID controller followed the demand reference input trajectory efficiently with minimal error steady state.

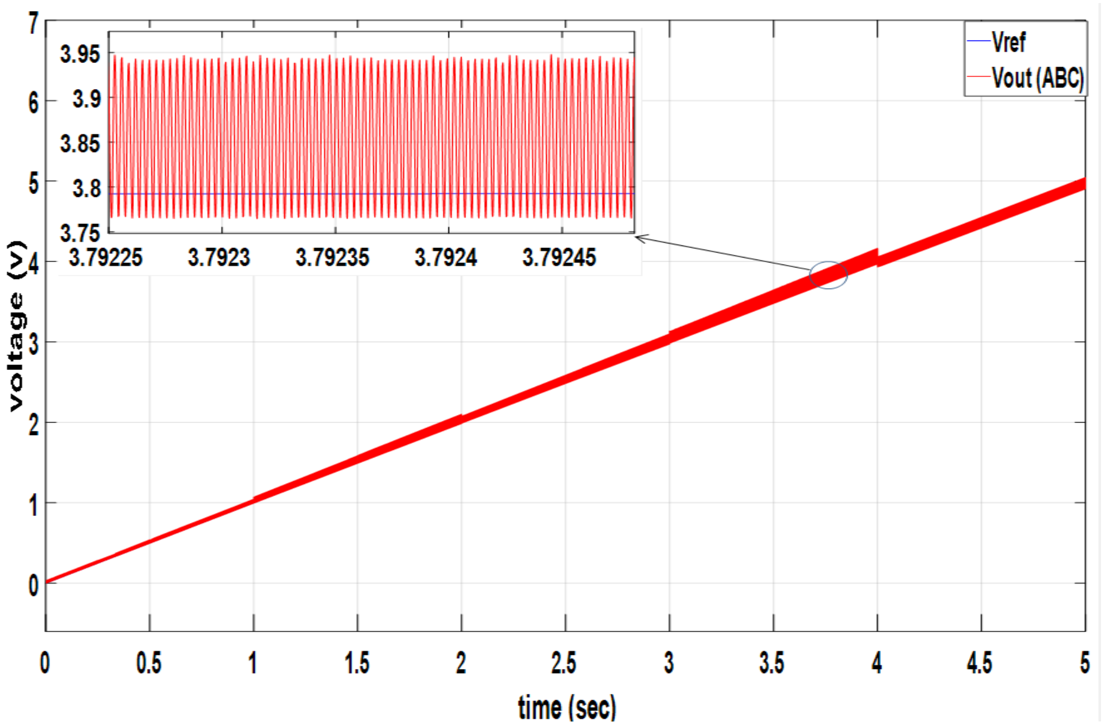


Figure 4.12: The response of source, reference and load disturbance for ABC-PID simulation result.

Table 4.15. illustrates the output characteristics of the Buck converter based on the simulation result in figure 4.12.

Table 4.15: The system characteristics for ABC case-IV

Parameters	Value
Steady state error (v)	0.1365
Peak to peak output ripple voltage (△V)	1.88%

Based on the simulation result of the classical Buck converter, it can ba said that again the ABC-PID controller can produce a faster and more accurate response compared with that of the PSO-PID controller.

4.2 Hybrid Buck Converter Simulation

In this sections, a switched inductor Buck convert system is presented a DC voltage converter, which should provide a faster drop output voltage compared with that of the classic Buck converter. The hybrid design of Buck converter control system was simulated using Matlab environment aiming to validate the proposed feedback PID controller. In this thesis, Matlab script was used to implement two optimization techniques namely, PSO and ABC, which are adopted to find optimum values for PID gain parameters. Simulink tool is utilized to simulated the proposed voltage controlled switched inductor Buck converter system in order to validate the voltage regulation performance of the optimized PID controller.

The value of the capacitor (C) and inductors (L1 and L2) of the Hybrid Buck converter were calculated based on the parameters in the Table 4.1. and their values was obtained as follows L_1=L_2=1.5×10^{-4} H, C=1.25×10^{-7} F.

4.2.1 Hybrid converter simulation based on PSO algorithm

In this section, three working cases are considered, which will be taken in detail, to verify the robustness of the proposed PID feedback control system for hybrid Buck converter. The proposed system hybrid regulator is simulated using Matlab/simulink tool. As in classic Buck converter system most of the model components are inserted from simulink power systems library, while the variable resistor is modeled using simulink simscape electrical components library.

Based on the PSO tuning method , the optimized PID controller parameters are given below:

K_p= 0.15 ,K_i=23, K_d=0.00005

Hybrid-PSO-case I: Steady state

In this working case, the simulink model of the switched-inductor Buck converter system based on PSO-PID controller is built using fixed values electric components. The simulink schematic of the hybrid scheme is presented in Figure 4.13. The parameters values of the model are listed in Table 4.16. Based on the Matlab command sim a connection between the Matlab script file, which is used to implement the PSO tuning algorithm for PID parameters, and the converter simulink model is investigated.

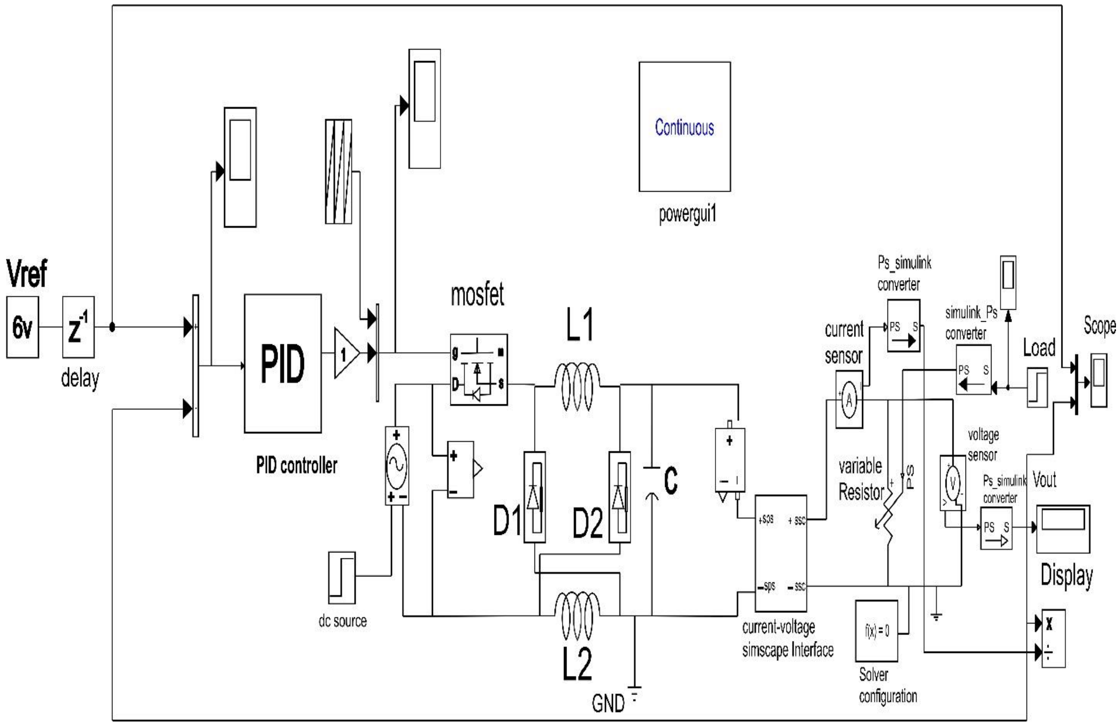


Figure 4.13: Simulink model of PSO-PID controller for Hybrid PSO-case I.

Table 4.16: Buck converter parameters for Hybrid PSO-case I.

Parameter	Symbol	Value
Input voltage	V_{in}	24v
Reference voltage	V_{ref}	6V
Inductance	L1 L2	1.5×10^{-4}H 1.5×10^{-4}H
Resistance	R	10Ω
Capacitance	C	1.25×10^{-7}F

Table 4.17: PSO algorithm parameters.

Parameter	Symbol	Value
Population size	P	20
No. of iterations	N	20
Congitive component	C_1	1.2
Social component	C_2	1.2
Max. speed	C	10
Max inertia weight	w_{max}	0.9
Min. Inertia weight	w_{min}	0.4

The optimization process using PSO algorithm is implemented based on the algorithm parameters listed in Table 4.17. Based on the optimized PID gain parameters, the output voltage of the hybrid Buck converter based on PSO algorithm is shown in Figure 4.14. It is clear from the mini-plot of the figure, that the optimized feedback PID control system succeeded to guide the hybrid Buck converter output voltage through the desired reference trajectory effectively. Compared with the corresponding classic converter response stated in figure 4.2, it is clear that there is an improvement in the overshoot parameters is achieved, however, the rise time,settling times are slower than that of the classic converter with error steady state is greater than the classic converter . The reason for this is that at charging state the same current passes in the two inductors (L_1 and L_2) that means that the equivalent inductor is the sum of the two inductors. The high value of an equivalent inductor causes an increase in the rise and settling times of the system response.

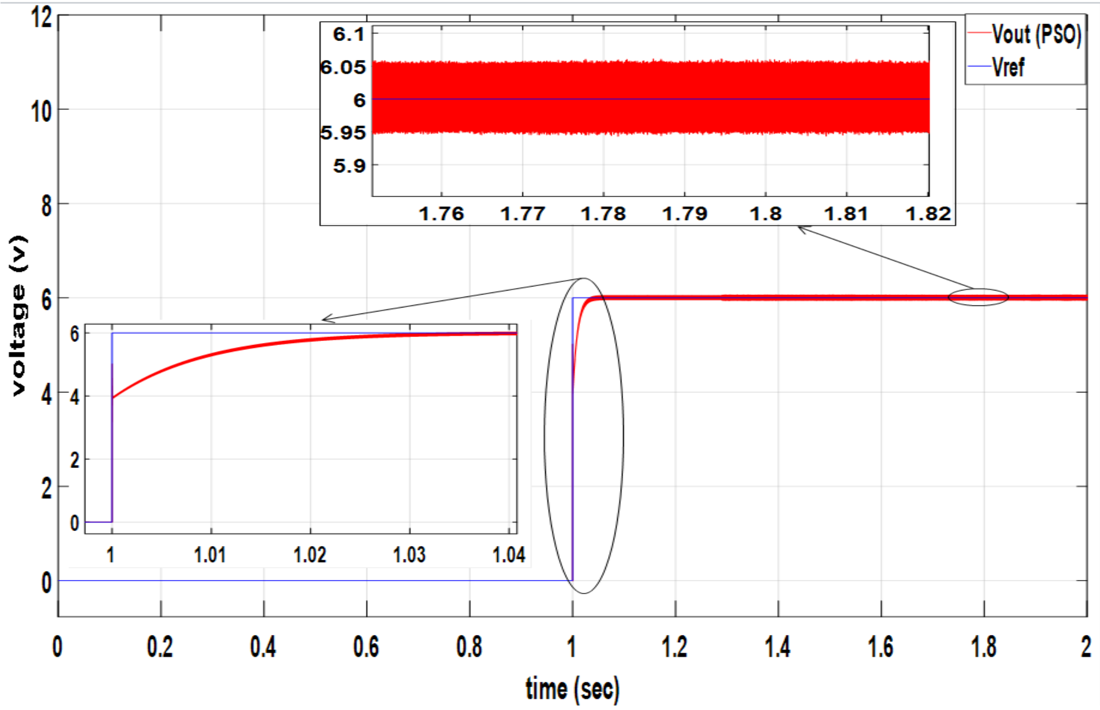


Figure 4.14: Response of converter system for hybrid PSO-PID case I.

Table 4.18 presents characteristics parameters of the converter output response , Based on the simulation result of the system shown in figure 4.14.

Table 4.18: The system characteristics for Hybrid PSO case-I

Parameters	Value
Average overshoot	1.0833%
Rise time (ms)	17
Settling time (ms)	36
Steady state error (v)	0.06
Peak to peak output ripple voltage (△V)	0.5%

Hybrid-PSO-case II: Reference voltage disturbance

In this simulation case, the regulation performance of the hybrid Buck converter is evaluated based on the parameters presented in Table 4.19 and using PSO-PID feedback control system. The simulink model of the hybrid regulator system based on a triangle reference voltage is depicted in Figure 4.15.

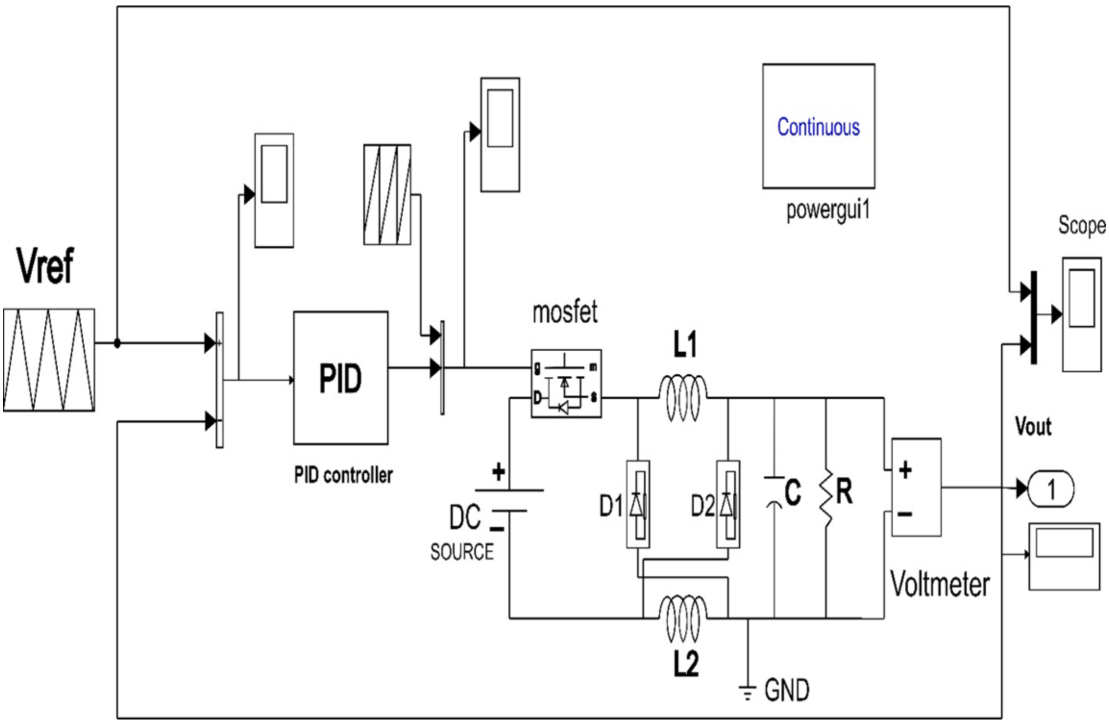


Figure 4.15: Simulink schematic of hybrid-PSO-case II.

Table 4.19: Electric parameters of hybrid Buck converter based on Hybrid-PSO-case II.

Parameter	Symbol	Value
Input voltage	V_{in}	24v
Reference voltage	V_{ref}	[0 6 0] v
Inductance	L1 L2	1.5×10^{-4}H 1.5×10^{-4}H
Resistance	R	10Ω
Capacitance	C	1.25×10^{-7}F

Figure 4.16 including its mini-plot shows the response of the hybrid converter based on a triangle desired voltage. It is obvious from the miniplot of the system response that the output voltage of the Buck converter followed the demand input voltage trajectory efficiently with fast rise and settling times. Compared with the corresponding classic converter response presented in figure 4.6 the hybrid converter based on PSO-PID controller showed a smoother response with lower steady state error.

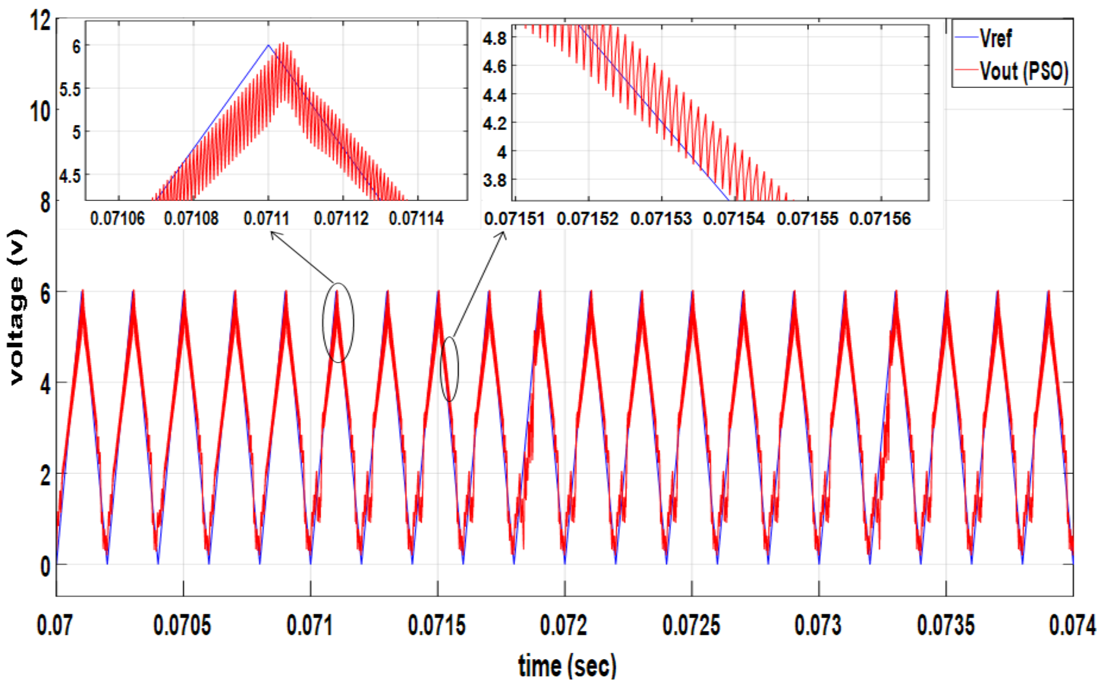


Figure 4.16: Response of hybrid PSO-PID controller under reference voltage disturbance.

Table 4.20 presents characteristics parameters of the converter output response, Based on the simulation result of the system shown in figure 4.16.

Table 4.20: The system characteristics for Hybrid PSO case-II

Parameters	Value
Average overshoot	0.5%
Steady state error (v)	0.35
Peak to peak output ripple voltage (△V)	2.5%

Hybrid-PSO-case III: Load resistance disturbance

A change in the load resistance value of the hybrid Buck converter is considered in this working case. It is worth considering that, the variable resistor is modeled using simscape electrical components library. A Current-Voltage simscape interface block is used to achieve a coupling between power systems and simscape components. This coupling unit performs a current source on the power systems components side and a voltage source on the load side. In the present simulation, the voltage regulation performance of the hybrid Buck converter using the proposed PSO-PID controller is investigated under the parameters values listed in Table 4.21. The simulink diagram of the hybrid Buck converter under load resistance disturbances is illustrated in Figure 4.17.

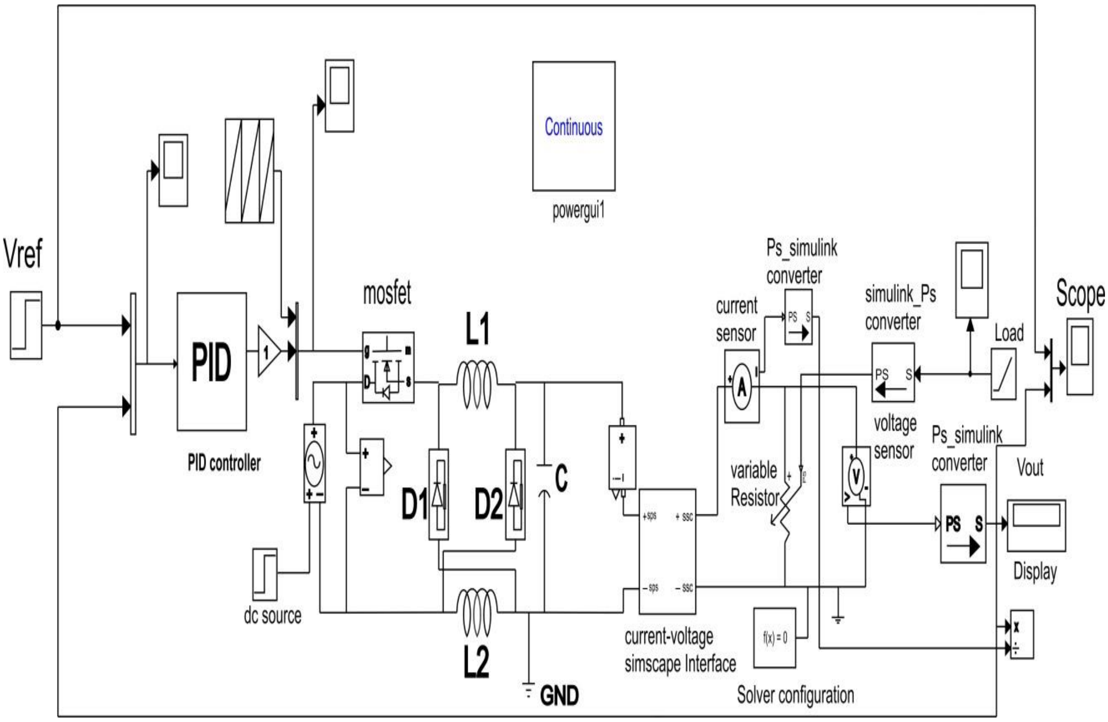


Figure 4.17: **The simulink model of Hybrid-PSO-case III using Load resistance disturbance**

Table 4.21: Circuit components of the hybrid Buck converter based on variable load resistance.

Parameter	Symbol	Value
Input voltage	V_{in}	24v
Reference voltage	V_{ref}	6V
Inductance	L1 L2	1.5×10^{-4}H 1.5×10^{-4}H
Resistance	R	(5-10) Ω
Capacitance	C	1.25×10^{-7}F

The output response of the hybrid Buck converter under changing in the load resistance is presented in Figure 4.18. Based on the minfigure of the system response, it can be said that the hybrid power converter based on PSO-PID controller is able to regulate its output signal effectively and deliver a stable and precise output voltage with minimal overshoot and minimal steady state error.

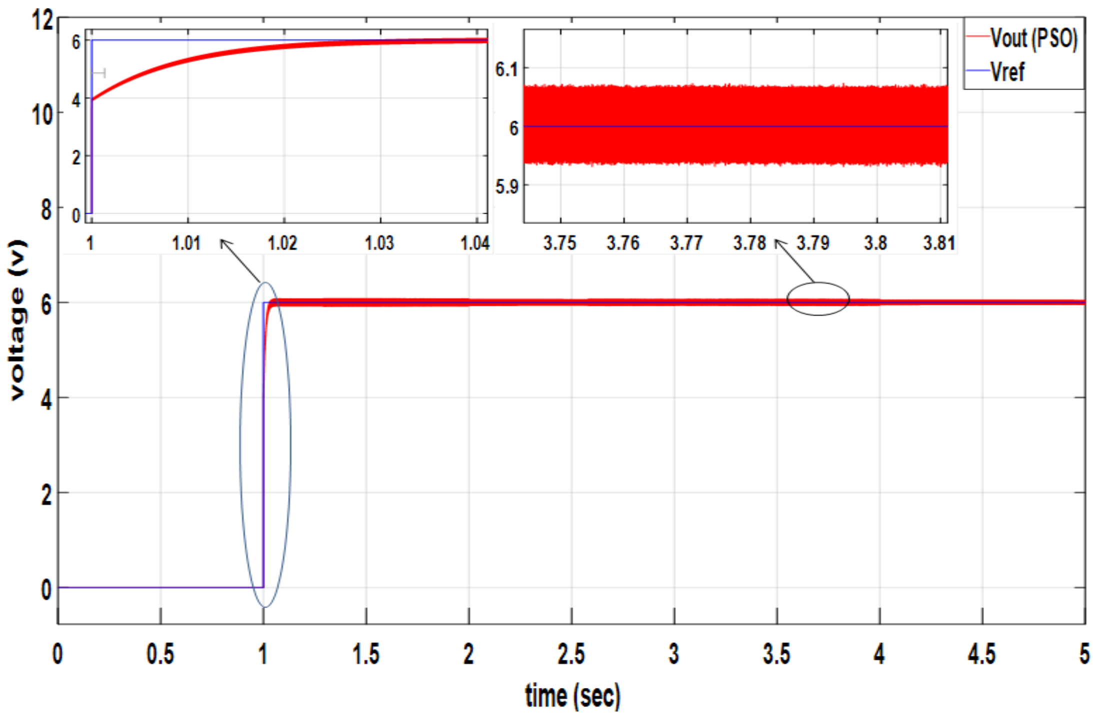


Figure 4.18: The response of load resistance disturbance for hybrid PSO-PID simulation result.

Table 4.22 illustrates the output charactrestics of the Buck converter Based on the simulation result in figure 4.18.

Table 4.22: The system characteristics for Hybrid PSO case-III

Parameters	Value
Average overshoot	1.1%
Rise time (ms)	12.5
Settling time (ms)	33
Steady state error (v)	0.065
Peak to peak output ripple voltage (△V)	0.083%

4.2.2 Hybrid Buck converter simulation based on ABC algorithm

This section follows the same structure of the previous section in terms of the cases considered in this thesis. three working cases are depended, which will be taken in detail, to verify the proposed PID feedback control system for hybrid Buck converter under the ABC algorithm. The model of the Buck voltage regulator is simulated using Matlab/simulink tool to evaluate the proposed ABC-PID controller.

After applying ABC optimization algorithm the tuned PID controller parameters are given below:

K_p= 0.0092 ,K_i=214, K_d=0.00155

Hybrid-ABC-case I: Stesdy state

In this case, constant values for the Buck converter parameters were used in the simulation. The simulink diagram of the hybrid Buck converter is the same as that of PSO based hybrid Buck converter as previously shown in Figure 4.13. The optimization process using ABC algorithm is implemented based on the algorithm parameters listed in Table 4.16. The output response of the hybrid Buck converter based on fixed circuit parameters values using ABC-PID is demonstrated in Figure 4.19. Based on the miniplots of figure 4.19, it can be observed that the hybrid Buck converter achieved a little oscillation, and delivered a stable output voltage efficiently with minimal error steady state.

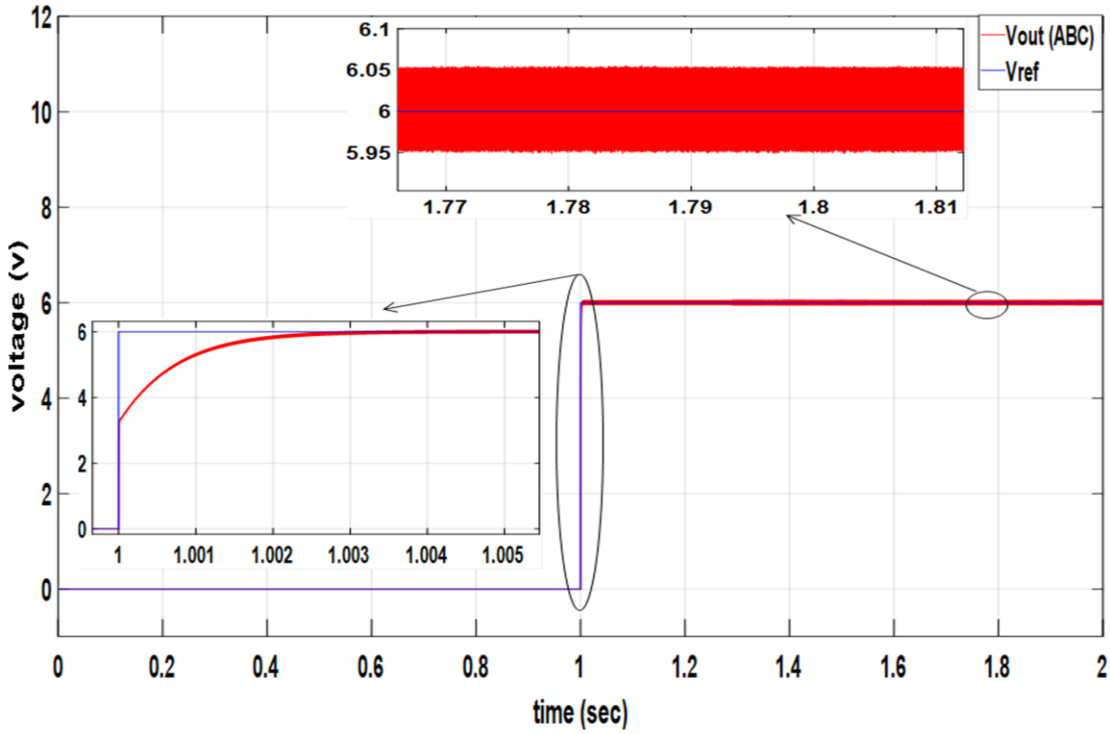


Figure 4.19: Response of ABC-PID based hybrid converter system without disturbances.

Table 4.23 presents characteristics parameters of the converter output, Based on the simulation result of the system shown in figure 4.19.

Table 4.23: The system characteristics for Hybrid ABC case-I

Parameters	Value
Average overshoot	0.95%
Rise time (ms)	1.2
Settling time (ms)	3
Steady state error (v)	0.052
Peak to peak output ripple voltage (△V)	0.066%

Hybrid-ABC-case II: Reference voltage disturbance

In the present case, the regulation performance of the hybrid Buck converter is evaluated based on triangle reference voltage. The simulink model of the system is the same simulink diagram of PSO-PID converter system as previously presented in Figure 4.15. The optimization process using ABC algorithm is implemented in Matlab software based on the algorithm parameters listed in Table 4.19. Figure 4.20 demonstrates the output voltage of the hybrid Buck converter with variable reference voltage based on ABC-PID controller. From the miniplots of the system response, it is clear that the controller forced the converter output to follow the desired input trajectory efficiently, where, the transient response of the captured voltage signal is fast .

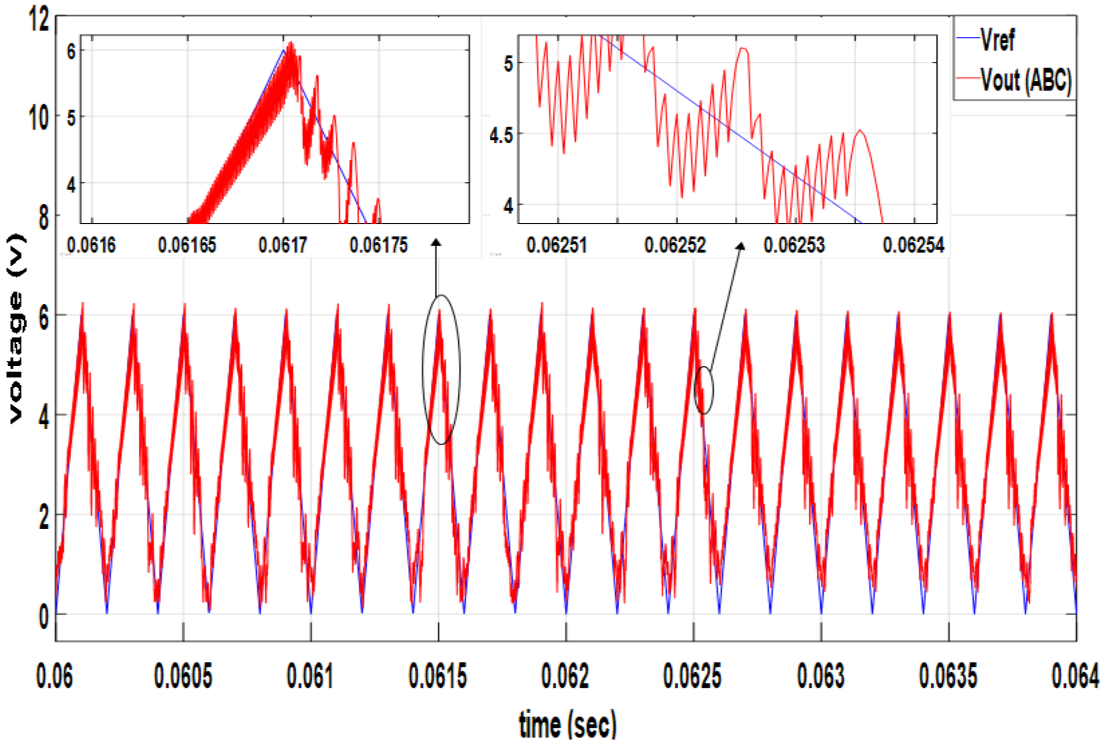


Figure 4.20: Response of ABC-PID based hybrid Buck converter system based on reference voltage disturbance.

Based on the simulation result of the system shown in figure 4.20., Table 4.24 presents characteristics parameters of the converter output response.

Table 4.24: The system characteristics for Hybrid ABC case-II

Parameters	Value
Average overshoot	1.66%
Steady state error (v)	0.6
Peak to peak output ripple voltage ($\triangle$V)	0.33%

Hybrid-ABC-case III: Load resistance disturbance

A change in the load resistance value of the hybrid Buck converter system is considered in this working case. In the present simulation case, the voltage regulation performance of the hybrid converter using the proposed ABC-PID controller is investigated under a linear variation in the load resistance. The simulink model of the hybrid Buck converter system based on ABC-PID controller is the same that of classic converter system as previously shown in Figure 4.17. The optimization process using ABC algorithm is implemented based on the algorithm parameters listed in Table 4.21. Figure 4.21 shows the output response of the hybrid Buck converter with varying load resistance. The miniplots of figure 4.21 result revealed that the proposed ABC-PID controller is able to regulate output signal of the hybrid regulation system effectively and deliver a stable and precise output voltage with minimal overshoot and minimal steady state error.

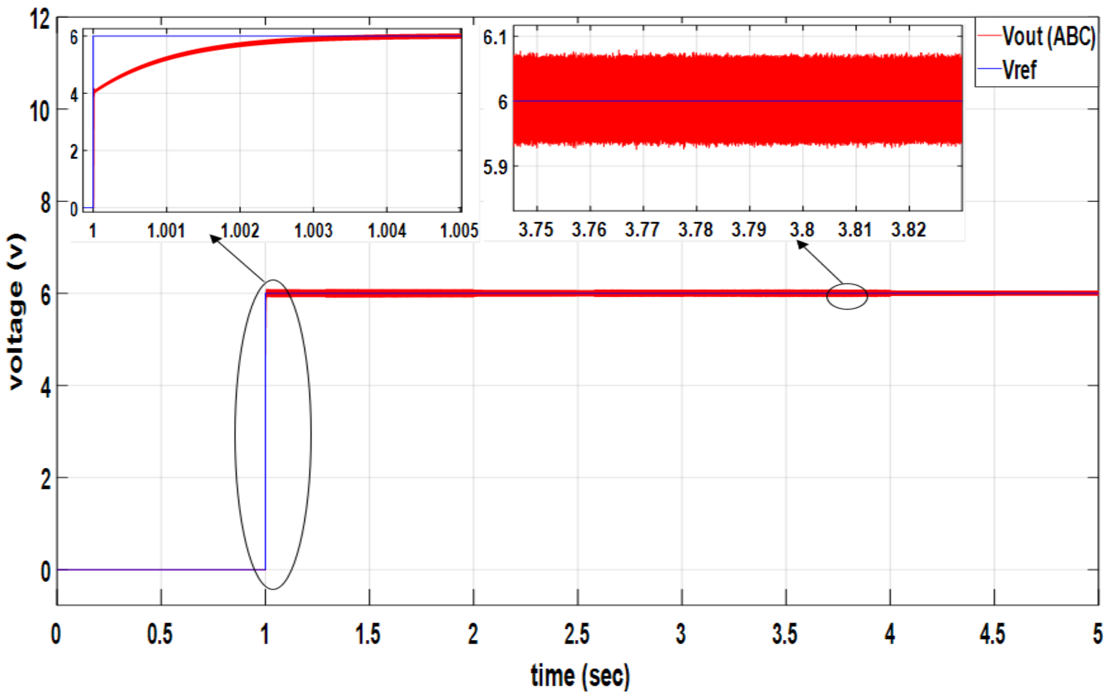


Figure 4.21: The response of the hybrid ABC-PID simulation result based on the load resistance disturbance.

Based on the simulation result of the system shown in figure 4.21., Table 4.25 presents characteristics parameters of the converter output response

Table 4.25: The system characteristics for Hybrid ABC case-III

Parameters	Value
Average overshoot	1.25%
Rise time (ms)	1.55
Settling time (ms)	3.7
Steady state error (v)	0.07
Peak to peak output ripple voltage (△V)	0.083%

Chapter five

Conclusions and Future Works

5.1 Conclusions

Buck converters have been extensively used in variety of industry and electronics applications. There are three main types of Buck converters namely; classic Buck converter, switch inductor Buck converter, and switch capacitor Buck converter. In this thesis, a classic Buck converter and switch inductor Buck converter were presented. PID controller was adopted in feedback voltage control system for classic and hybrid Buck convertors. The voltage regulation performance of the proposed PID controller was optimized through using two optimization methods namely, PSO and ABC algorithms. These algorithms were used to find optimum values for the controller gain parameters. The two classes Buck converters with closed-loop voltage control system are designed, modelled and then simulated using Matlab/ Simulink environment to validate the optimized PID controller system. The simulated time responses of the two types of Buck converters using PSO-PID and ABC-PID controllers were presented and compared based on transient and steady state characteristics parameters, which include rise time, settling time, maximum overshoot and steady state error.

the voltage regulation performance of the classic and hybrid Buck converters were evaluated under three expected working disturbances, which are varying in source voltage, reference voltage and load resistance, to validate the robustness of the proposed PSO/ABC tuned PID controller.The simulation results revealed that the output voltage of Buck converters with uncertainties under action of the PSO-PID and ABC-PID controllers succeeded to follow the desired reference voltage trajectories effectively. The output of the voltage controlled Buck converters had fast response with minmal seady state error. However, the response of the ABC-PID controller was faster than that of PSO-PID controller.

5.2 Future Work

The prospective research includes the following:

1. The presented switch inductor Buck converter with disturbances will be implemented in real time using a Digital Signal Processor (DSP) device to validate the proposed PID controller for fast drop voltage applications. As the DSP can be adopted to implement control algorithms based on very high frequency signals in shorter time compared with the Arduino device. In addition, to its ability to implement more complex signal conditioning operations, like noise filtering and reduction the influence of the ripple problem in the converter output voltage.
2. Performance development of step down DC-DC Buck converter by using Silicon-Carbede (SiC) technology, which can be successfully adopted for high voltage and temperature applications. The Buck converter system based on the SIC technology can achieve a more stable conversion performance based on hard working conditions like high pressure, vibration and temperature as well as its adjusting performance is good and stable in high voltage applications.

APPENDIX (A)

Arduino Device

Arduino is an easy-to-use and open-source hardware and software that was invented in 2005 [84]. Their hardware boards have the ability to read inputs from sensors and/or buttons and turn them into outputs. These outputs, in turn, can activate a machine or devise, lighting a Light Emitting Diode (LED), and many other actions [84]. Arduino boards are programmable meaning that it is easy to tell the hardware what to do through the instructions that are written on the microcontroller on the Arduino board. The recent years have witnessed a great revolution in the Arduino systems due to its intensive use in a variety of projects by developers, engineers, students, artists, programmers, hobbyists, to mention a few [85]. Arduino was introduced at the Ivrea Interaction Design Institute for fast prototyping and enables students and learners who do not have a background in programming and electronics [84]. In fact, Arduino has been used to satisfy new needs and challenges, differentiating its offer from simple 8-bit boards to products for the Internet of Things (IoT) applications, embedded environments, wearable things, and 3D printing [85]. The main reasons behind adopting Arduino technology are inexpensive, run different kinds of operating systems such as Windows, Mac, and Linux, clear and simple programming tools, and open-source in terms of hardware and software.

Arduino boards can be easily connected to different electronic devices and machines such as sensors, Global Positioning Systems (GPSs), detectors, etc. The Arduino's main function is to perform a control process on its inputs aiming to produce outputs aiming at performing a particular task [86].

There are many types of Arduino boards that are varied according to the abilities and the features available in the board. Table (1.A) presents different types and features of Arduino boards [86]. Currently, several types of Arduino are available in the markets for different applications such as Arduino Uno (R3), Arduino Micro and Nano, Arduino Bluetooth, Arduino Diecimila, RedBoard Arduino Board, Arduino Due, LilyPad Arduino Board, Arduino Ethernet, Arduino Mega (R3) Board, Arduino Leonardo Board, Arduino Pro Mic, Arduino Robot, Arduino Esplora, and Arduino Zero [84][85][86].

Table 1.A: Characteristics of Arduino boards

Arduino Board	Analogue Input	Analogue Output	Digital I/O	Memory	Processor
Arduino Uno	6	0	14	2KB SRAM, 32KB flash	16Mhz ATmega328
Arduino Due	12	2	54	96KB SRAM, 512KB flash	84MHz AT91SAM3X8E
Arduino Mega	16	0	54	8KB SRAM, 256KB flash	16MHz ATmega2560
Arduino Leonardo	12	0	20	2.5KB SRAM, 32KB flash	16MHz ATmega32u4

In this thesis, Arduino Mega 2560 is used to perform the real-time implementation of the proposed voltage regulation system for DC-DC Buck converter. This electronic device as shown in figure (1-A) has 16 analog inputs and 54 I/O pins, 4 UARTs (serial ports), a USB connection, 16 MHz crystal oscillator, ICSP header, power jack, and reset button [84]. Based on these parts and features, this kind of Arduino systems can provide all the support that is needed by the PID controller. Moreover, it can be simply connected to a PC through the USB port.

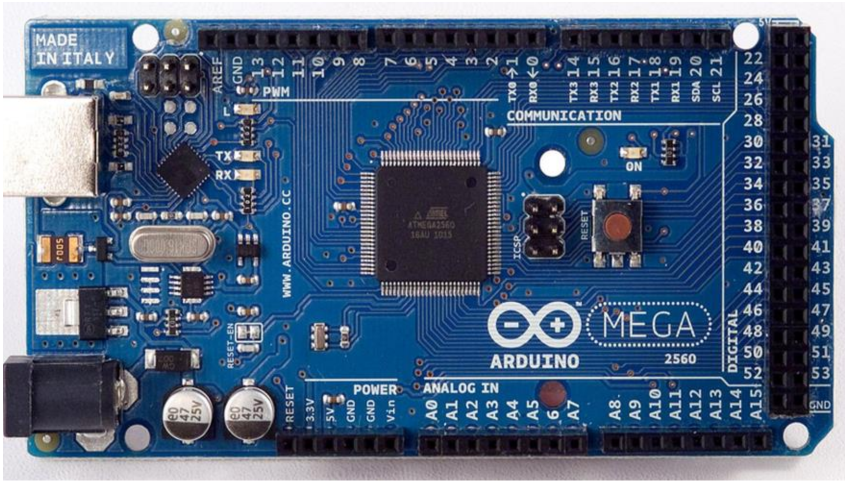


Figure 1.A: Arduino AT mega board.

The technical specifications and physical dimensions of the Arduino ATMega 2560 are listed in Table (2-A). Figure (2.A) shows the pin diagram of the Arduino ATMega 2560. The USB can be the power source of the Arduino Mega, an external power supply can also be its power source. The process of selecting the power source can automatically be performed. The external power source can be provided by a battery or AC-DC adapter. The latter can be connected by plugging a 2.1mm center-positive plug into the Power Jack of the board. An external supply of 6 to 20V can operate the board. When using more than 12V, an overheat may be caused by the regulator, which leads to damage the board. Besides, when the voltage is less than 7V, the 5V pin may provide less than 5V. Practically, this can lead to having an unstable board. Hence, it is recommended to operate the board in the range of 7V to 12V [87].

Furthermore, the memory of the Atmega 2560 is 256 KB, which is used to storing codes. Out of this space, 8 KB is dedicated for SRAM, 8

KB for the bootloader, and 4 KB for the EEPROM. Moreover, the 54 digital pins of the ATmega2560 are used as an input or output. This can be performed by functions (e.g., digital Read and digital Write) under 5 volts of operation. A pin has the ability to provide or receive 40 mA (maximum). The 16 analog inputs can provide 10 bits of resolution [87][88].

In terms of communication with PCs, the Atmega 2560 has four hardware UARTs for TTL (5V) serial communication with the PC. Also, the software Arduino includes a serial monitor. This software enables textual to be sent/received to/from the board. The Arduino software can also be used in programming the board. The Arduino programming can be performed using different kinds of programming languages (e.g., C, C++, Matlab, Python) [87][88][89].

Table 2.A: Technical specifications of the Arduino Mega 2560

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage	7-12V
Input Voltage	6-20V
Digital I/O Pins	54 (15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB (8 KB dedicated for bootloader)
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz
LED_Builtin	13
Length	101.52mm
Width	53.3mm
Weight	37g

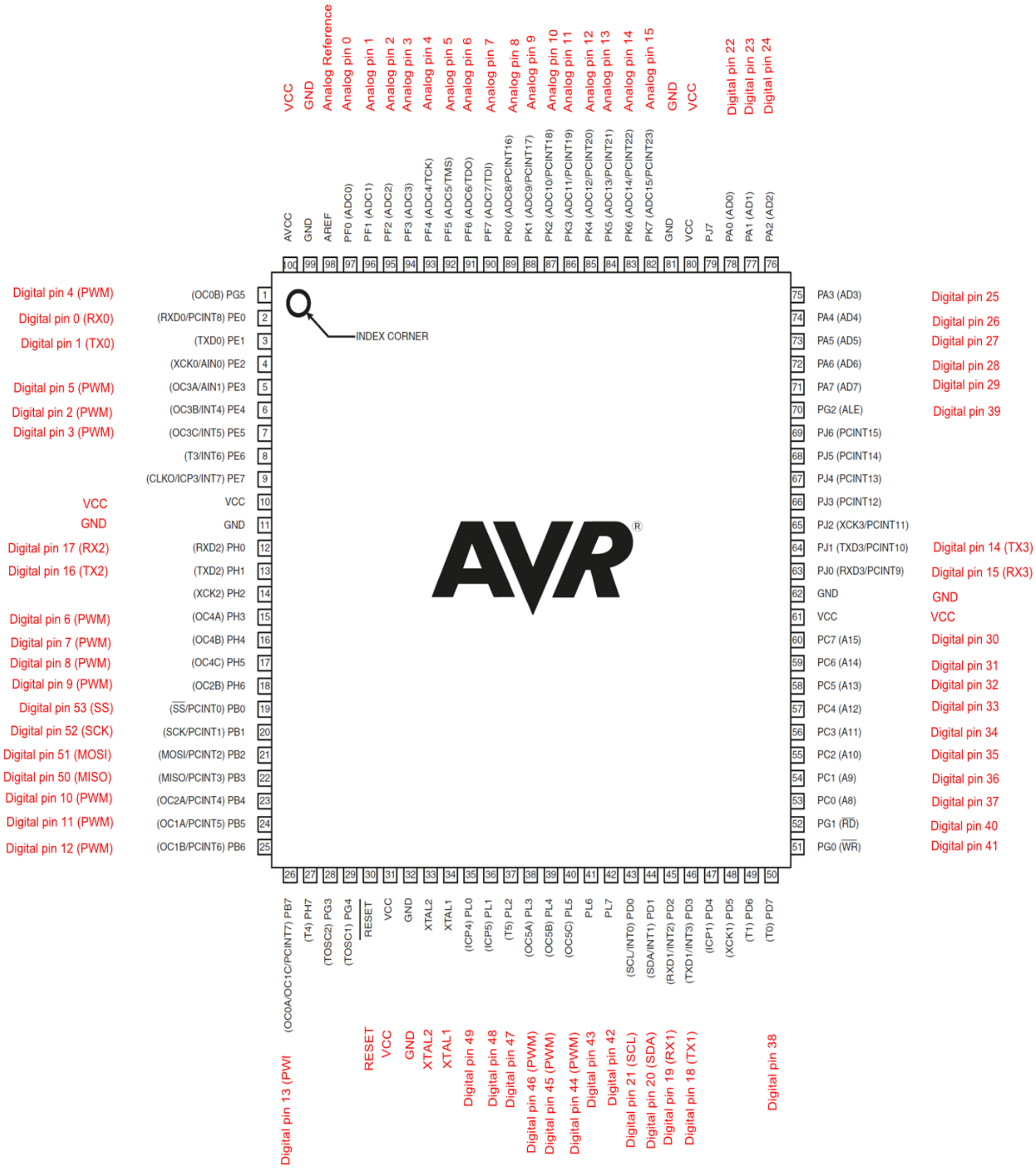


Figure 2.A: Arduino AT mega 2560 pins diagram.

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ألخلاصة

المغيرالخافض هو نوع من محولات DC-DC ذات الوضع المغير والتي تستخدم على نطاق واسع في دوائر الكترونيات القدرة. يتم استخدامه لتوفير جهد أخراج منخفض المستوى للأحمال في تطبيقات مختلفة. في هذه الرسالة ، يتم استخدام نوعين من المغيرات الخافضة ، مغيرات كلاسيكية ومغيرات هجينية ، لتوصيل الجهد المطلوب لأحمال المغير. يتم استخدام وحدة تحكم PID القياسية في نظام التحكم في التغذية العكسية لكلا النوعين. تم تصميم مغير رياضيًا ومن ثم تم تصميم وحدة التحكم PID لتنظيم جهد الاخراج لمغير الخافض.

في هذا الرسالة ، تم تطوير وحدة التحكم PID باستخدام خوارزميات ضبط مجموعة الجسيمات (PSO) وخوارزميات ضبط مستعمرة النحل الاصطناعية (ABC) ، والتي يتم استخدامها للحصول على القيم المثلى لمعاملات كسب وحدة التحكم. استنادًا إلى معاملات الكسب المحسّنة ، يمكن للمغير الخافض المعتمد على PID إرسال جهد أخراج ثابت للأحمال. يتم استخدام بيئة Matlab / Simulink في عملية محاكاة المغيرات الخافضة الكلاسيكية والهجينة.

يتم فحص سلوك التحويل لأنظمة منظم المغيرالخافض بناءً على جميع ظروف العمل المتوقعة ، والتي تشمل التباين في جهد المصدر والجهد المرجعي ومقاومة الحمل ، للتحقق من قوة وحدة التحكم PID المضبوطة PSO / ABC المقترحة. تمت محاكاة المغير الخافض الكلاسيكي باستخدام برنامج Matlab لتقييم أداء المغير الخافض مع حدوث اضطراب. تعتمد عملية التقييم على معاملات الخصائص القياسية ، والتي تتكون من وقت الصعود ووقت التنظيم وovershoot وخطأ الحالة المستقرة. تظهر نتائج المحاكاة ميزة متحكمات PSO-PID و ABC-PID في توجيه جهد أخراج المغير من خلال مسارات الإدخال المطلوبة بشكل فعال. ومع ذلك ، يمكن للمغير الخافض المستند إلى وحدة تحكم PID المضبوطة ABC أن يوفر جهد اخراج مستقر أكثرمن ذلك المعتمد على وحدة تحكم PSO-PID.
الأحمال.

يتم أيضًا محاكاة المغيرالهجين مع الاضطرابات باستخدام أداة Matlab / Simulink ومقارنة أدائه مع نتائج وحدة التحكم PSO-PID. تظهر نتائج المحاكاة أن المغير الخافض الهجين المعتمد على طريقة ضبط ABC يمكن أن يوفر فولتية هبوط اسرع مع أدنى خطأ في الحالة المستقرة مقارنة بالمغير الخافض الكلاسيكي.

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

﴿ فَتَعَالَى اللَّهُ الْمَلِكُ الْحَقُّ وَلَا تَعْجَلْ بِالْقُرْآنِ مِنْ
قَبْلِ أَنْ يُقْضَى إِلَيْكَ وَحْيُهُ وَقُلْ رَبِّ زِدْنِي عِلْمًا ﴾

صَدَقَ اللَّهُ العَظِيم

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وزارة التعليم العالي والبحث العلمي

جامعة نينوى

كلية هندسة الالكترونيات

قسم الإلكترونيك

دراسة مقارنة للمغير الخافض التقليدي والهجيني المحسن

محمد نواف احمد عبيد

رسالة ماجستير علوم في هندسة الإلكترونيك

بإشراف

د. أحمد ذنون يونس

د. أبراهيم خلف محمد

1443 هـ 2021 م

دراسة مقارنة للمغير الخافض

التقليدي والهجيني المحسن

رسالة تقدم بها

محمد نواف احمد عبيد

إلى

مجلس كلية هندسة الالكترونيات -جامعة نينوى

وهي جزء من متطلبات نيل شهادة الماجستير

علوم في هندسة الالكترونيك

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